

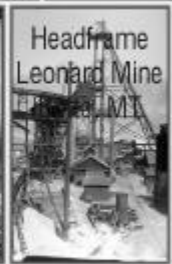
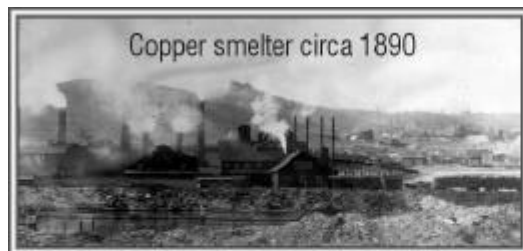
EPA/DOE

MINE WASTE TECHNOLOGY PROGRAM

Technology Testing for Tomorrow's Solutions



2000 ANNUAL REPORT



Cover photos courtesy of C. Owen Smithers

EPA/DOE

MINE WASTE TECHNOLOGY PROGRAM

2000 ANNUAL REPORT

Prepared by:

MSE Technology Applications, Inc.
P.O. Box 4078
Butte, Montana 59702

Mine Waste Technology Program
Interagency Agreement Management Committee
IAG ID NO. DW89938870-01-0

Prepared for:

U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research Laboratory
26 W. Martin Luther King Drive
Cincinnati, Ohio 46268

and

U.S. Department of Energy
National Energy Technology Laboratory
P.O. Box 10940
Pittsburgh, Pennsylvania 15236-0940
Contract No. DE-AC22-96EW96405

CONTENTS

	Page
Vision Statement for the Butte Mine Waste Technology Program	1
Program Manager's Executive Summary	3
Introduction	5
Program Overview	7
Organizational Structure	9
Activities	11
Descriptions, Accomplishments, and Future Direction	11
Activity I Overview—Issues Identification	11
Activity II Overview—Quality Assurance	11
Activity III Overview—Pilot-Scale Demonstrations	12
Project 3 Sulfate-Reducing Bacteria Demonstration	12
Project 8 Underground Mine Source Control	14
Project 10 Surface Waste Piles—Source Control	15
Project 12 Sulfate-Reducing Bacteria Reactive Wall Demonstration	18
Project 12A Calliope Mine Internet Monitoring System	23
Project 13 Hydrostatic Bulkhead with Sulfate-Reducing Bacteria	26
Project 14 Biological Cover Demonstration	26
Project 15 Tailings Source Control	29
Project 16 Integrated Passive Biological Treatment Process Demonstration	30
Project 19 Site In Situ Mercury Stabilization Technologies	31
Project 20 Selenium Removal/Treatment Alternatives	32
Project 21 Integrated Process for Treatment of Berkeley Pit Water	35
Project 22 Phosphate Stabilization of Mine Waste Contaminated Soils	36
Project 23 Revegetation of Mining Waste Using Organic Amendments and Evaluate the Potential for Creating Attractive Nuisances for Wildlife	37
Project 24 Improvements in Engineered Bioremediation of Acid Mine Drainage	40
Activity IV Overview	41
Project 11 Pit Lake System Characterization and Remediation for Berkeley Pit—Phase II	42
Project 12 An Investigation to Develop a Technology for Removing Thallium from Mine Wastewaters	43
Project 13 Sulfide Complexes Formed from Mill Tailings Project	44
Project 14 Artificial Neural Networks as an Analysis Tool for Geochemical Data	44
Project 15 Imaging Spectroscopy—An Initial Investigation	45
Project 16 Pit Lake System Characterization and Remediation for Berkeley Pit—Phase III	45

Activity V Overview—Technology Transfer	46
Activity VI Overview—Training and Education	47
Financial Summary	49
Completed Activities	50
Activity III	
Project 1 Remote Mine Site Demonstration	50
Project 2 Clay-Based Grouting Demonstration	51
Project 4 Nitrate Removal Demonstration	51
Project 5 Biocyanide Demonstration	52
Project 6 Pollutant Magnet	53
Project 7 Arsenic Oxidation	54
Project 9 Arsenic Removal	55
Project 11 Cyanide Heap Biological Detoxification Demonstration	56
Project 17 Lead Abatement Demonstration	56
Project 18 Gas-Fed Sulfate-Reducing Bacteria Berkeley Pit Water Treatment	57
Activity IV	
Project 1 Berkeley Pit Water Treatment	58
Project 2 Sludge Stabilization	59
Project 3 Photoassisted Electron Transfer Reactions Research	59
Project 3A Photoassisted Electron Transfer Reactions for Metal-Complexed Cyanide	60
Project 3B Photoassisted Electron Transfer Reactions for Berkeley Pit Water	61
Project 4 Metal Ion Removal from Acid Mine Wastewaters by Neutral Chelating Polymers	62
Project 5 Removal of Arsenic as Storable Stable Precipitates	63
Project 7 Berkeley Pit Innovative Technologies Project	64
Project 8 Pit Lake System—Characterization and Remediation for the Berkeley Pit	64
Project 9 Pit Lake System—Deep Water Sediment/Pore Water Characterization and Interactions	65
Project 10 Pit Lake System—Biological Survey of Berkeley Pit Water	66
Key Contacts	67

VISION STATEMENT FOR THE BUTTE MINE WASTE TECHNOLOGY PROGRAM

THE PROBLEM

Mining activities in the United States (not counting coal) produce between 1 and 2 billion tons of mine waste annually. These activities include extraction and beneficiation of metallic ores, phosphate, uranium, and oil shale. Over 130,000 of these noncoal mines, concentrated largely in nine western states, are responsible for polluting over 3,400 miles of streams and over 440,000 acres of land. About seventy of these sites are on the National Priority List for Superfund remediation. In the 1985 Report to Congress on the subject, the total noncoal mine waste volume was estimated at 50 billion tons, with 33% being tailings, 17% dump/heap leach wastes and mine water, and 50% surface and underground wastes. Since many of the mines involve sulfide minerals, the production of acid mine drainage (AMD) is a common problem from these abandoned mine sites. The cold temperatures in the higher elevations and heavy snows frequently prevent winter site access. The combination of acidity, heavy metals, and sediment have severe detrimental environmental impacts on the delicate ecosystems in the West.

THE PHILOSOPHY/VISION

End-of-pipe treatment technologies, while essential for short-term control of environmental impact from mining operations, are a stop-gap approach for total remediation. Efforts need to be made on improving the end-of-pipe technologies to reduce trace elements to low levels for applications in ultra-sensitive watersheds and for reliable operation in unattended, no power situations. The concept of pollution prevention, emphasizing at-source control and resource recovery, is the approach of choice for the long-term solution. Our objective in the Butte Mine Waste Technology Program is not to

assess the environmental impacts of the mining activities, but it is to develop and prove technologies that provide satisfactory short- and long-term solutions to the remedial problems facing abandoned mines and the ongoing compliance problems associated with active mines, not only in Montana but throughout the United States.

THE APPROACH

There are priority areas for research, in the following order of importance:

Source Controls, Including In Situ Treatments and Predictive Techniques

It is far more effective to attack the problem at its source than to attempt to deal with diverse and dispersed wastes, laden with wide varieties of metal contaminants. At-source control technologies, such as sulfate-reducing bacteria; biocyanide oxidation for heap leach piles; transport control/pathway interruption techniques, including infiltration controls, sealing, grouting, and plugging by ultramicrobiological systems; and AMD production prediction techniques should strive toward providing a permanent solution, which of course is the most important goal of the program.

Treatment Technologies

Improvements in short-term end-of-pipe treatment options are essential for providing immediate alleviation of some of the severe environmental problems associated with mining, and particularly with abandoned ore mines. Because immediate solutions may be required, this area of research is extremely important to effective environmental protection.

Resource Recovery

In the spirit of pollution prevention, much of the mining wastes, both AMD (e.g., *over 25 billion*

gallons of Berkeley Pit water) and the billions of tons of mining/beneficiation wastes, represent a potential resource as they contain significant quantities of heavy metals. While remediating these wastes, it may be feasible to incorporate resource recovery options to help offset remedial costs.

THE PARTNERSHIPS

In these days of ever-tightening budgets, it is important that we leverage our limited funding with other agencies and with private industry. We are aggressively working to integrate the Butte program with the U.S. Department of Energy Resource Recovery Project to leverage both budgets. The Bureau of Land Management and Forest Service participate by providing sites for demonstrations of the technologies. It is important where these technologies have application to active mining operations to achieve cost-sharing partnerships with the mining industry to test the technologies at their sites. Within the U.S. Environmental Protection Agency, the Butte program is coordinated and teamed, where appropriate, with the Superfund Innovative Technology Evaluation (SITE) program to leverage the funding and maximize the effectiveness of both programs. Several joint projects are underway, and more are planned.

A considerable resource and willing partner is the University system (such as Montana Tech of the University of Montana, University of Montana–Missoula, Montana State University–Bozeman, and the Center for Biofilm Engineering), which can conduct the more basic type of research essential to kinetics

characterization and bench-scale test more experimental, less developed concepts at minimal cost to the program, while at the same time providing environmental education that will be useful to the region and to the Nation. The Butte Mine Waste Technology Program supports cooperative projects between the educational system and the mining industry, where teams of students conduct research of mine site-specific problems, often with monetary support from the industry. The results are made available to the industry as a whole and to the academic community.

THE SCIENCE

The research program is peer-reviewed semiannually by the Technical Integration Committee (TIC), who technically reviews all ongoing and proposed projects. The TIC is composed of technical experts from the cooperating agencies, academia, environmental stakeholders, and industry and their consultants.

Roger C. Wilmoth
Chief, Industrial Multimedia Branch
Sustainable Technology Division
National Risk Management Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
(MS 445)
26 W. Martin Luther King Drive
Cincinnati, OH 45268

PROGRAM MANAGER'S EXECUTIVE SUMMARY

The Mine Waste Technology Program (MWTP) Annual Report for fiscal 2000 summarizes the results and accomplishments for the various activities within the Program. The MWTP has met its goals by providing assistance to the public and forming cooperative teams drawn from government, industry, and private citizens. The funds expended have returned tangible results, providing tools for those faced with mine waste remediation challenges.

After 10 years, everyone involved with MWTP can look with pride to the Program's success. Technology development has proceeded successfully through the efforts of MSE Technology Applications, Inc. (MSE) and its prime subcontractor Montana Tech.

MSE has developed twenty-seven field-scale demonstrations, several of which are attracting attention from the stakeholders involved in the cleanup of mine wastes.

Montana Tech has developed fourteen bench-scale projects, five of which are ongoing during 2000.

Numerous activities are associated with the development of a field-scale demonstration. Among these activities are acquiring federal and state permits, securing liability limiting access agreements, developing and adhering to health and safety operation plans, and complying with the National Environmental Policy Act and other federal and state environmental oversight statutes.

The Program has received substantial support from state and federal agencies, the mining industry, environmental organizations, and numerous associations interested in mining and development of natural resources at state, regional, and national levels.

Montana Tech continued the post-graduate degree program with a mine waste emphasis. The quality of short courses offered by Montana Tech is becoming highly recognized among the mine waste remediation community.

The MWTP recognizes its major accomplishments and looks forward to providing new and innovative technologies; meeting the challenges of mine waste remediation; and providing economical, permanent solutions to the nation's mineral waste problems.

Creighton Barry
MSE MWTP Program Manager

INTRODUCTION

Mining waste generated by active and inactive mining production facilities and its impact on human health and the environment are a growing problem for Government entities, private industry, and the general public. The nation's reported volume of mine waste is immense. Presently, there are more than sixty sites on the U.S. Environmental Protection Agency's National Priorities List.

Environmental impacts associated with inactive and abandoned mines are common to mining districts around the country, as shown in Table 1.

Total estimated remediation costs for these states range from \$4 to \$45 billion.

Health effects from the predominate contaminants in mine waste range from mild irritants to proven human carcinogens, such as cadmium and arsenic. The large volume of mine wastes and consequential adverse environmental and human health effects indicates an urgency for cleanup of abandoned, inactive, and active mining facilities. The environmental future of the United States depends in part on the ability to deal effectively with mine waste problems of the past and present, and more importantly, to prevent mine waste problems in the future.

According to a 1985 report to Congress, mining and related activities generate anywhere from 1 to

billion tons of waste each year with a current total waste volume of 50 billion tons. Of this total volume, approximately 85% is attributed to copper, iron ore, uranium, and phosphate mining and related activities. Approximately one-half of the waste generated is mining waste, one-third is tailings, and the balance consists of dump/heap leaching wastes and mine water.

The fiscal year (FY) 1991 Congressional Appropriation allocated \$3.5 million to establish a pilot program in Butte, Montana, for evaluating and testing mine waste treatment technologies. The Mine Waste Technology Program (MWTP) received additional appropriations of \$3.5 million in FY91, \$3.3 million in FY94, \$5.9 million in FY95, \$2.5 million in FY96, \$7.5 million in FY97, \$6.0 million in FY98 and FY99, and \$4.3 million in FY00.

The projects undertaken by this Program focus on developing and demonstrating innovative technologies at both the bench- and pilot-scale that treat wastes to reduce their volume, mobility, or toxicity. To convey the results of these demonstrations to the user community, the mining industry, and regulatory agencies, MWTP includes provisions for extensive technology transfer and educational activities. This report summarizes the progress MWTP made in FY00.

Table 1. Number and types of sites and abandoned mine lands in Western Region.

State	Estimated Number of Sites or Land Areas	Classification and Estimated Number
Alaska	10,910 sites	mine dumps - 1,000 acres disturbed land - 27,680 acres mine openings - 500 hazardous structures - 300
Arizona	95,000 sites	polluted water - 2,002 acres mine dumps - 40,000 acres disturbed land - 96,652 acres mine openings - 80,000
California	11,500 sites	polluted water - 369,920 acres mine dumps - 171 acres mine openings - 1,685
Colorado	20,229 sites covering 26,584 acres	polluted water 830,720 acres mine dumps - 11,800 acres disturbed land - 13,486 acres mine openings - 20,229 hazardous structures - 1,125
Idaho	8,500 sites covering 18,465 acres	polluted water - 84,480 acres mine dumps - 3,048 acres disturbed land - 24,495 acres mine openings - 2,979 hazardous structures - 1,926
Michigan	400-500 sites	Accurate information not available.
Montana	19,751 sites covering 11,256 acres	polluted water - 715,520 acres mine dumps - 14,038 acres disturbed land - 20,862 acres mine openings - 4,668 hazardous structures - 1,747
Nevada	400,000 sites	Accurate information not available.
New Mexico	7,222 sites covering 13,585 acres	polluted water - 44,160 acres mine dumps - 6,335 acres disturbed land - 25,230 acres mine openings - 13,666 hazardous structures - 658
Oregon	3,750 sites	polluted water - 140,800 acres mine dumps - 180 acres disturbed land - 61,000 acres mine openings - 3,750 hazardous structures - 695
South Dakota	4,775 acres	Accurate information not available.
Texas	17,300 acres	Accurate information not available.
Utah	14,364 sites covering 12,780 acres	polluted water - 53,120 acres mine dumps - 2,369 acres disturbed land - 18,873 acres mine openings - 14,364 hazardous structures - 224
Wisconsin	200 acres	Accurate information not available.
Wyoming	5,000 acres	Accurate information not available.
<p>Information was collected from the following sources and is only an estimate of the acid mine drainage problem in the West.</p> <div> <div> -Bureau of Land Management -Bureau of Mines -Mineral Policy Center -National Park Service -U.S. Department of Agriculture </div> <div> -U.S. Department of the Interior -U.S. Forest Service -U.S. Geological Survey -U.S. General Accounting Office -Western Governor's Association Mine Waste Task Force Study </div> </div>		

PROGRAM OVERVIEW

FISCAL 2000 PROGRAM

This Mine Waste Technology Program (MWTP) annual report covers the period from October 1, 1999, through September 30, 2000. This section of the report explains the MWTP organization and operation.

MISSION

The mission of MWTP is to provide engineering solutions to national environmental issues resulting from the past practices of mining and smelting metallic ores. In accomplishing this mission, MWTP develops and conducts a program that emphasizes treatment technology development, testing and evaluation at bench- and pilot-scale, and an education program that emphasizes training and technology transfer. Evaluation of the treatment technologies focuses on reducing the mobility, toxicity, and volume of waste; implementability; short- and long-term effectiveness; protection of human health and the environment; community acceptance; and cost reduction.

The statement of work provided in the Interagency Agreement between the U.S. Environmental Protection Agency and the U.S. Department of Energy identifies six activities to be completed by MWTP. The following descriptions identify the key features of each and the organization performing the activity.

ACTIVITY I: ISSUES IDENTIFICATION

Montana Tech of the University of Montana (Montana Tech) is documenting mine waste technical issues and innovative treatment technologies. These issues and technologies are then screened and prioritized in volumes related to a specific mine waste problem. Technical issues of primary interest are Mobile Toxic Constituents—Water/Acid Generation; Mobile Toxic Constituents—Air, Cyanide, Nitrate,

Arsenic, Pyrite, Selenium, and Thallium; and Pit Lakes. Wasteforms reviewed related to these issues include point- and nonpoint-source acid drainage, abandoned mine acid drainage, stream-side tailings, impounded tailings, priority soils, and heap leach-cyanide/acid tailings. In addition, under this task Montana Tech produced a CD-ROM based summary of the Program in two volumes—Annual Report and Activities in Depth. The CDs can be obtained from the personnel listed in the Contacts Section of this report. The Annual Report data is also available on the web at www.epa.gov/ORD/NRMRL/std/mtb.

ACTIVITY II: GENERIC QUALITY ASSURANCE PROJECT PLAN

In 2000, MSE Technology Applications, Inc. (MSE) prepared a Quality Management Plan that provides specific instructions for data gathering, analyzing, and reporting for all MWTP activities. MSE develops project-specific quality assurance project plans and provides oversight for all quality assurance activities.

ACTIVITY III: PILOT-SCALE DEMONSTRATIONS

Pilot-scale demonstration topics were chosen after a thorough investigation of the associated technical issue was performed, the specific wasteform to be tested was identified, peer review was conducted, and sound engineering and cost determination of the demonstration were formulated.

MSE continued thirteen field-scale demonstrations during fiscal 2000. Three field demonstrations were completed: Cyanide Heap Biological Detoxification; Lead Abatement; and Gas-Fed Sulfate-Reducing Bacteria for Berkeley Pit Treatment. One project, Phosphate Stabilization of Heavy Metals Contaminated Mine Waste Yard Soils, was begun.

ACTIVITY IV: BENCH-SCALE EXPERIMENTS

Montana Tech successfully completed three projects during fiscal 2000: 1) Pit Lake System—Character-ization and Remediation for the Berkeley Pit; 2) Pit Lake System—Deep Water Sediments/Pore Water Characterization and Interactions; and 3) Pit Lake System—Biological Survey of the Berkeley Pit. Four projects were begun: 1) and investigation to develop a technology for removing thallium from mine waste; 2) sulfide complexes formed from depositing mill tailings into a pit lake; 3) artificial neural networks as an analysis tool for geochemical data; and 4) Pit Lake System Characterization and Remediation of Berkeley Pit—Phase III. In addition, Project 11, Pit Lake System Characterization and Remediation for Berkeley Pit—Phase II, which assesses the effect of organic carbon, wall rock/water interactions, bacteria for natural remediation, and the effect of redepositing neutral tailings into the Berkeley Pit was in progress.

ACTIVITY V: TECHNOLOGY TRANSFER

MSE is responsible for preparing and distributing reports for MWTP. These include routine weekly, monthly, quarterly, and annual reports; technical progress reports; and final reports for all MWTP activities. MSE also publicizes information developed under MWTP in local, regional, and national publications. Other means of information transfer include public meetings, workshops, and symposiums.

ACTIVITY VI: EDUCATIONAL PROGRAMS

Montana Tech has developed a post-graduate degree program with a mine waste emphasis. The program contains elements of geophysical, hydrogeological, environmental, geochemical, mining and mineral processing, extractive metallurgical, and biological engineering.

ORGANIZATIONAL STRUCTURE

MANAGEMENT ROLES AND RESPONSIBILITIES

Management of the Mine Waste Technology Program (MWTP) is specified in the Interagency Agreement. The roles and responsibilities of each organization represented are described below. The MWTP organizational chart is presented in Figure 1.

U.S. ENVIRONMENTAL PROTECTION AGENCY

The Director of the National Risk Management Research Laboratory (NRMRL) in Cincinnati, Ohio, is the principal U.S. Environmental Protection Agency Office of Research and Development representative on the Interagency Agreement Management committee. NRMRL personnel are responsible for management oversight of technical direction, quality assurance, budget, schedule, and scope.

DEPARTMENT OF ENERGY

The Director of the National Energy Technology Laboratory (NETL) is the principal U.S. Department of Energy (DOE) representative on the Interagency Agreement Management committee. NETL personnel provide contract oversight for MWTP. MSE Technology Applications, Inc. (MSE) is responsible to NETL for adherence to environmental, safety and health requirements; regulatory requirements; National Environmental Protection Act requirements, and conduct of operations of all projects.

MSE TECHNOLOGY APPLICATIONS, INC.

MSE, under contract with DOE, is the principal performing contractor for MWTP. The MWTP Program Manager is the point of contact for all mine waste activities. The Program Manager is responsible for program management and coordination, program status reporting, funds distribution, and communications.

An MSE project manager has been assigned to each MWTP project and is responsible to the MWTP Program Manager for overall project direction, control, and coordination. Each project manager is responsible for implementing the project within the approved scope, schedule, and cost. MSE also provides all staff necessary for completing Activities III and V and oversight of Activities II, III, IV, and VI.

MONTANA TECH OF THE UNIVERSITY OF MONTANA

As a subcontractor to MSE, Montana Tech of the University of Montana is responsible to the MWTP Program Manager for all work performed under Activities I, II, IV, and VI. The responsibility for overall project direction, control, and coordination of the work to be completed by Montana Tech is assigned to the MWTP Montana Tech Project Manager.

TECHNICAL INTEGRATION COMMITTEE

The Technical Integration Committee reviews progress in meeting the goals of MWTP and to alert the Interagency Agreement Management Committee to pertinent technical concerns. The committee provides information on the needs and

requirements of the entire mining waste technology user community and assists with evaluating technology demonstrations as well as technology transfer. This committee is comprised of representatives from both the public and private sectors.

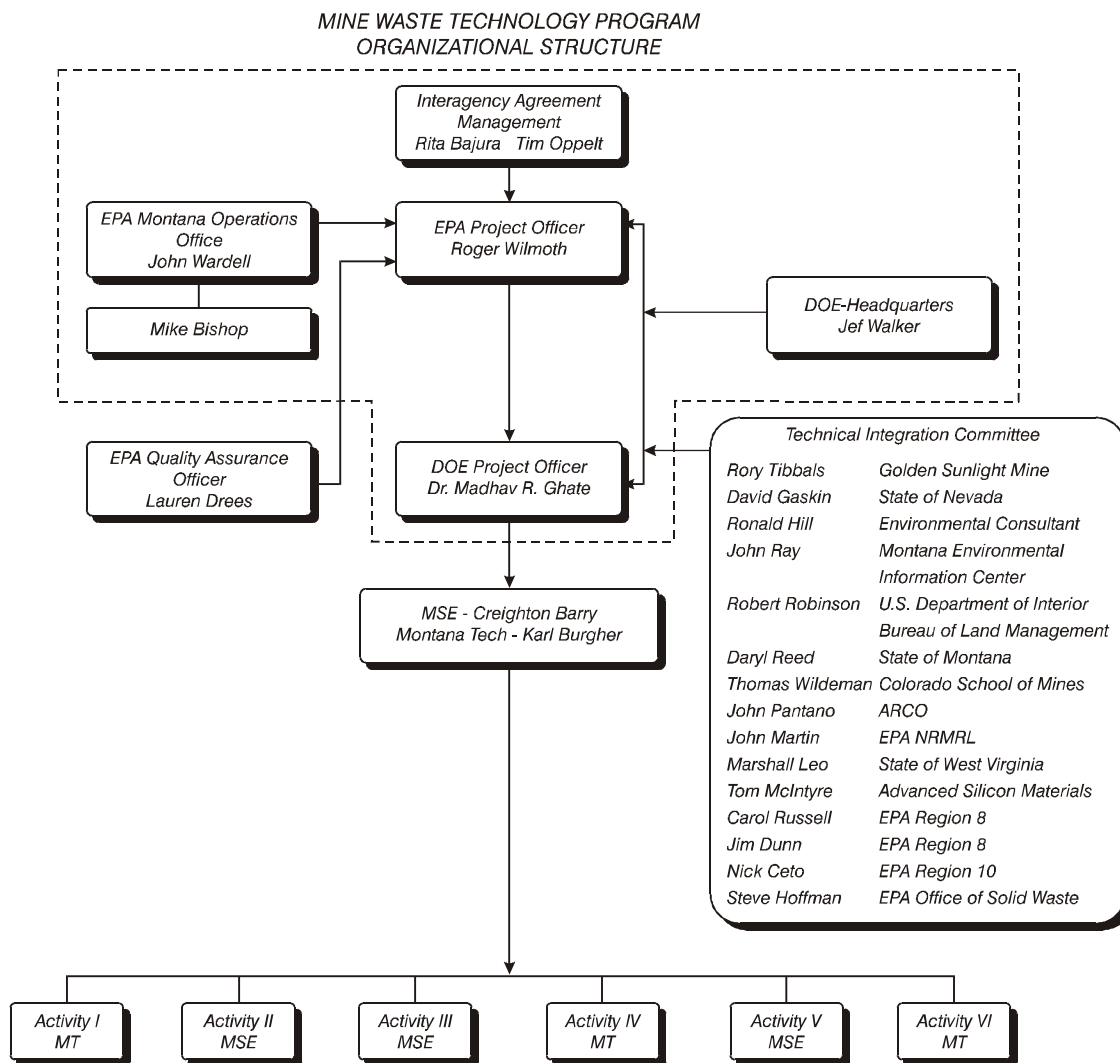


Figure 1. MWTP organizational chart.

ACTIVITIES

DESCRIPTIONS, ACCOMPLISHMENTS, AND FUTURE DIRECTION

This section describes the Mine Waste Technology Program (MWTP) Activities I through VI and includes project descriptions, major project accomplishments during fiscal 2000, and future project direction.

ACTIVITY I OVERVIEW ISSUES IDENTIFICATION

This activity focuses on documenting mine waste technical issues and identifying innovative treatment technologies. Issues and technologies are screened and prioritized in volumes related to a specific mine waste problem/market.

Following completion of a volume, appendices are prepared. Each appendix links a candidate technology with a specific site where such a technology might be applied. The technology/site combinations are then screened and ranked.

Technical Issue Status

The status of the volumes approved for development includes:

- Volume 1, Mobile Toxic Constituents—Water and Acid Generation, complete.
- Volume 2, Mobile Toxic Constituents—Air, complete.
- Volume 3, Cyanide, complete.
- Volume 4, Nitrate, complete.
- Volume 5, Arsenic, complete.

- Volumes 1-5 Summary Report, complete.
- Volume 6, Pyrite, complete.
- Volume 7, Selenium, complete.
- Volume 8, Thallium, complete.
- Volume 9, Pit Lakes, in progress.

The status of the appendices for approved projects includes:

- Volume 1, Appendix A (Remote Mine Site), complete.
- Volume 1, Appendix B (Grouting), complete.
- Volume 1, Appendix C (Sulfate-Reducing Bacteria), complete.
- Volume 3, Appendix A (Biocyanide), complete.
- Volume 4, Appendix A (Nitrate), complete.

ACTIVITY II OVERVIEW QUALITY ASSURANCE

The objective of this activity is to provide support to individual MWTP projects by ensuring all data generated is legally and technically defensible and that it supports the achievement of individual project objectives. The primary means of carrying out this activity is the Quality Assurance Project Plan, which is written for each project. This plan specifies the quality requirements the data must meet, clearly states the project objectives, describes all sampling and measurement activities, and contains standard operating procedures, when applicable. Other functions of this activity include reviewing technical systems, validating data, implementing corrective action, and reporting to project management.

ACTIVITY III OVERVIEW PILOT-SCALE DEMONSTRATIONS

The objective of this activity is to demonstrate innovative and practical remedial technologies at selected waste sites, a key step in proving value for widespread use and commercialization.

Technologies and sites are selected primarily from the prioritized lists generated in the Volumes from Activity I, or they may be a scale-up from bench-scale experiments conducted under Activity IV.

ACTIVITY III, PROJECT 3: SULFATE-REDUCING BACTERIA DEMONSTRATION

Project Overview

Acid generation typically accompanies sulfide-related mining activities and is a widespread problem. Acid is produced chemically, through pyritic mineral oxidation, and biologically, through bacterial metabolism. This project focuses on a source-control technology that has the potential to significantly retard or prevent acid generation at affected mining sites. Biological sulfate reduction is being demonstrated at an abandoned hard-rock mine site where acid production is occurring with associated metal mobility.

Technology Description

For aqueous waste, this biological process is generally limited to the reduction of dissolved sulfate to hydrogen sulfide and the concomitant oxidation of organic nutrients to bicarbonate. The particular group of bacteria chosen for this demonstration, sulfate-reducing bacteria (SRB), require a reducing environment and cannot tolerate aerobic conditions for extended periods. These bacteria require a simple organic nutrient.

This technology has the potential to reduce the contamination of aqueous waste in three ways. First, dissolved sulfate is reduced to hydrogen sulfide through metabolic action by the SRB. Next, the hydrogen sulfide reacts with dissolved metals forming insoluble metal sulfides. Finally,

the bacterial metabolism of the organic substrate produces bicarbonate, increasing the pH of the solution and limiting further metal dissolution.

At the acid-generating mine site chosen for the technology demonstration, the Lilly/Orphan Boy Mine near Elliston, Montana, the aqueous waste contained in the shaft is being treated by using the mine as an in situ reactor. An organic nutrient was added to promote growth of the organisms. This technology will also act as a source control by slowing or reversing acid production. Biological sulfate reduction is an anaerobic process that will reduce the quantity of dissolved oxygen in the mine water and increase the pH, thereby, slowing or stopping acid production.

The shaft of the Lilly/Orphan Boy Mine was developed to a depth of 250 feet and is flooded to the 74-foot level. Acid mine water historically discharged from the portal associated with this level.

Pilot-scale work at the MSE Technology Applications, Inc., Testing Facility in Butte was performed in fiscal 1994 prior to the field demonstration. The objective of these tests was to determine how well bacterial sulfate reduction lowers the concentration of metals in mine water at the shaft temperature (8 °C) and pH (3).

Status

During fiscal 2000, the field demonstration was again monitored on a regular basis. Figure 2 presents a cross-section of the mine and technology installation.

During the past year of monitoring, the data generally demonstrated a decrease in metals concentrations (see Figure 3), with the exception of manganese, which SRBs do not effectively remove. An increase in metals was observed during spring runoff as occurred in prior years; however, the levels decreased when flow rates returned to normal. Field demonstration monitoring has been ongoing for 6 ½ years. Monitoring is scheduled to be completed in June 2001.

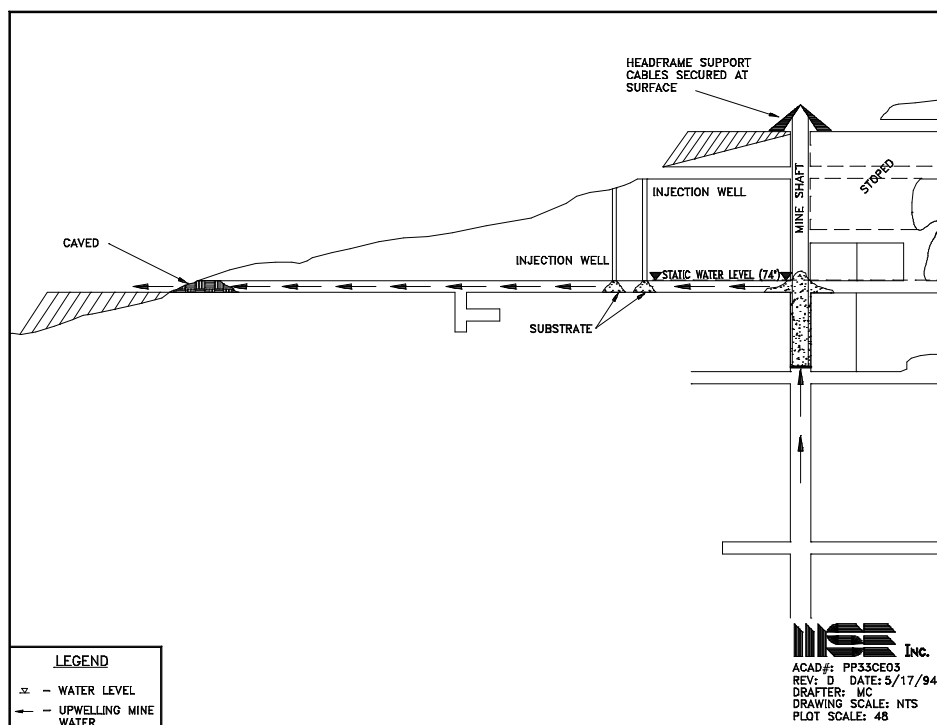


Figure 2. Cross-section of the Lilly/Orphan Boy Mine and the technology installation.

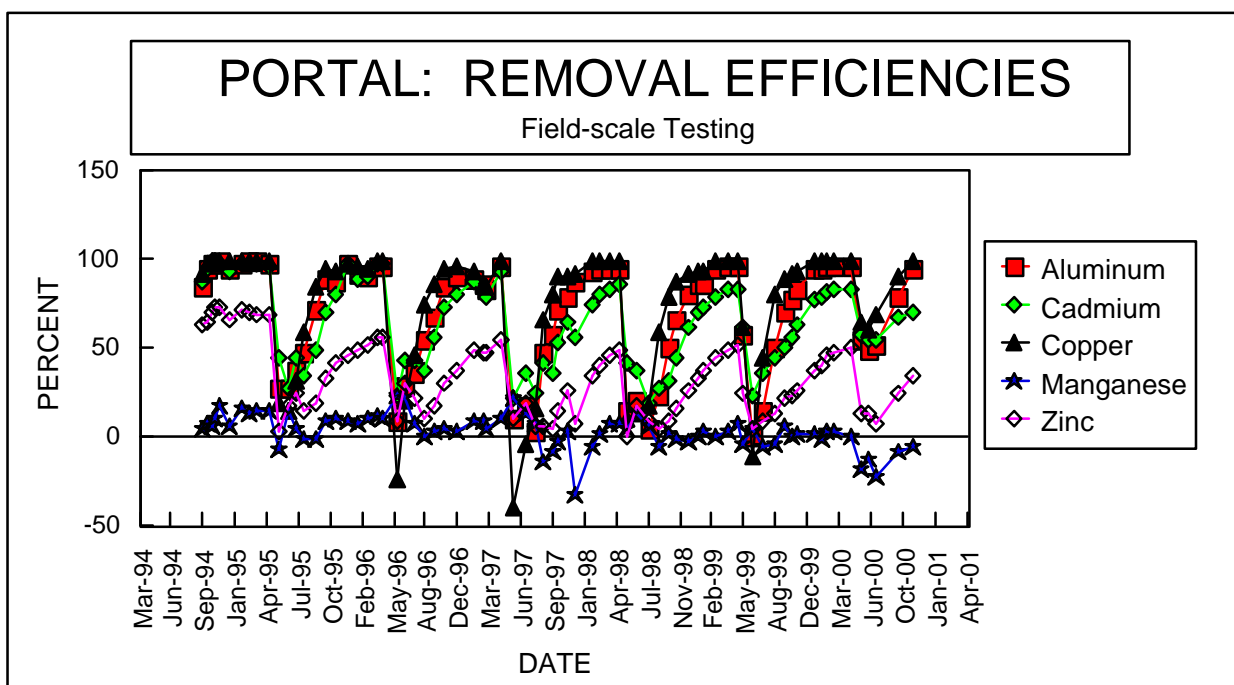


Figure 3. Metal removal efficiency at the Lilly/Orphan Boy Mine.

ACTIVITY III, PROJECT 8: UNDERGROUND MINE SOURCE CONTROL

Project Overview

A significant environmental problem at abandoned underground mines occurs when the influx of water contacts sulfide ores and forms acid and metal-laden mine discharge. The Underground Mine Source Control Project demonstrated that grout materials can be used to reduce and/or eliminate the influx of water into the underground mine system by forming an impervious barrier that results in reduced, long-term environmental impacts of the abandoned mine.

Technology Description

Ground water flow is the movement of water through fractures, fissures, or intergranular spaces in the earth. Some of the fractures are naturally occurring, others were the result of blasting during mining.

For this demonstration, a closed-cell, expandable polyurethane grout was injected into the fracture system that intercepts the underground mine workings. The demonstration consists of three phases: 1) extensive site characterization; 2) source control material identification and testing; and 3) source control material emplacement.

Phase One, completed in 1999, consisted of characterization studies, including hydrogeological,

geological, geochemical, and geophysical information gathering directly related to the mine and its operational history.

Phase Two encompassed source control material testing. Approximately 40 materials were tested according to ASTM methods for acid resistiveness, shear strength, plasticity, compressive strength, compatibility, and viscosity. The source control grout material selected for injection was Hydro Active Combi Grout, a closed-celled, expandable polyurethane grout manufactured by de neef Construction Chemicals, Inc. When compared to a cement-based source control material, this material offered the following advantages: greater retention of plasticity; less deterioration due to the acidic conditions and during rock movement; and better rheological characteristics.

Status

The Miller Mine near Townsend, Montana, was selected for the demonstration because the underground workings were accessible, it has a point-source discharge into the underground workings, the slightly acidic inflow is laden with heavy metals, and the inflow could be potentially controlled using the source control technology.

Phases One and Two were completed in March 1999. Phase Three, the field emplacement (shown in Figure 4), was completed in October 1999.

First year monitoring results indicate that the water flow into the underground mine was reduced from 10 to 15 gpm to approximately 1 to 1.2 gpm as a result of Phase III field emplacement.



Figure 4. Grout emplacement in the underground mine workings.

ACTIVITY III, PROJECT 10: SURFACE WASTE PILES—SOURCE CONTROL

Project Overview

Surface waste piles from mining operations were historically placed in drainage basins in front of the haulage tunnel. Surface water in the drainage, discharge from the mine, and precipitation usually contacted the waste pile. The water came in contact with the sulfide ore in the pile and infiltrated through the pile, where acid formed and the water became metal-laden. This water percolated from the toe of the pile and flowed into the closest surface water. The objective of this Mine Waste Technology Program demonstration was to provide source control technologies that could be applied in situ, meaning that the pile is stabilized in place and not excavated and moved to another location for stabilization. By using strategically applied in situ source control technologies, there will be a decrease in water infiltrating through the pile and ground water contact with surface waste pile material, thereby, decreasing the environmental impact.

Technology Description

Surface waste piles from historical mining activity, in many cases, consist of broken, low-grade, sulfide ores. When water and oxygen contact the sulfide ores, acid is formed, resulting in increased levels of dissolved metals in the water associated with the pile. The source of the water infiltrating the pile is usually precipitation onto the pile and/or from surface water (i.e., discharge water from a mine adit, stream flow, or in some instances ponded stream/discharge water). When the water discharges from the surface waste pile, it is acidic and metal-laden causing a significant environmental problem.

Usually in such situations, the surface waste pile is excavated and placed in a designed repository. However, this can be expensive, and in some instances, excavation of the pile or construction of a repository is not feasible. In certain instances, in situ application of source control technologies at a surface waste pile is the optimal solution. The source control technologies are strategically placed into the surface waste pile such that the infiltration of surface water and ground water flow through the pile are eliminated or reduced, resulting in a reduction of acidic, metal-laden water.

The demonstration consists of three phases: 1) site characterization; 2) source control materials testing; and 3) field emplacement.

Phase One, site characterization, included geochemical, geological, hydrogeological, and mineralogical studies that provided information directly related to the surface waste pile, the mine, the regional water system, and past operational procedures.

Phase Two, source control materials testing, was performed to determine if select source control material were acid resistant, was affected by wet/dry or freeze/thaw cycling, and if it would be impervious once it was emplaced onto the surface waste pile. The physical characteristics of the surface waste pile material were also defined in the bench-scale laboratory setting.

Status

The project site for this demonstration is the Peerless Mining Property located south of Rimini, Montana. The site was selected because of its size, hydraulic characteristics, and its water quality (see Figure 5). A major factor in the selection of the site was that it had an acidic, metal-laden, point-source discharge flowing from the toe of the

surface waste pile, and the upgradient water sources were of better quality and near neutral pH.

Phases One and Two were finalized by March 26, 1999. Phase Three, field emplacement, was initiated in September 1999 and finalized in November 1999. At the Peerless Mine, both surface water and ground water contacted the surface waste pile material and contributed to the acid mine drainage formation. Figure 6 shows the French drain system constructed to hydraulically control the ground water flow at the site.

The French drain was placed upgradient of the surface waste pile allowing the ground water to be transported away from the acid forming material. Figure 7 shows a spray-applied cover being applied to reduce the infiltration of precipitation through the pile. The spray-applied cover material used at the site (see Figure 8) was a flexible, urethane grout called KOBathane 4990, manufactured by General Polymers, Inc.

Long-term monitoring results indicate that the water quality of the seep flowing from the toe of the surface waste pile was improved. After the technology emplacement, the dissolved metal concentrations for zinc, cadmium, and copper were below the National Drinking Water Maximum Contaminant Standards.



Figure 5. The Peerless Mine surface waste pile before the technology demonstration.



Figure 6. French drain installation.



Figure 7. Flexible, urethane grout being sprayed directly on the surface waste pile.



Figure 8. Peerless Mine surface waste pile after partially sprayed with the urethane grout.

ACTIVITY III, PROJECT 12: SULFATE-REDUCING BACTERIA REACTIVE WALL DEMONSTRATION

Project Overview

Thousands of abandoned mine sites in the western United States impact the environment by discharging acid mine drainage (AMD) to surface water or ground water. Acid mine drainage is formed when sulfide-bearing minerals, particularly pyrite, produce oxygen and water in a chemical reaction that results in an increased acidity of the water (lowered pH), and increased concentration of dissolved metals and sulfate.

At many abandoned mine sites in the West, conventional treatment strategies for AMD (e.g., lime neutralization) are not feasible because of the remoteness of the mine locations, insomuch as a lack of a power source and limited site accessibility in winter. Sulphate-reducing bacteria (SRB) are capable of reducing the sulfate to sulfide, decreasing the load of dissolved metals in the effluent by precipitating metals as sulfides, and increasing the pH of the effluent. To demonstrate the feasibility of using SRB passive technology for

mitigation of AMD emanating from the toe of a waste rock pile, three bioreactors were built at the abandoned Calliope Mine site located near Butte, Montana.

Technology Description

The Calliope mine site includes a collapsed adit discharging water into a large (66,000 cubic yards) waste rock pile. This relatively good quality water flows over the top of the waste rock and accumulates in a small lower pond at the toe of the pile. The AMD is mostly produced by atmospheric water that infiltrates the waste rock pile and reappears on the surface at the toe of the pile enriched in metals and with a pH of 2.6. This AMD also flows to the pond where it mixes with good quality water and lowers its pH. A portion of the water that accumulates in the pond has been diverted for treatment to three engineered bioreactors that were built at the site to demonstrate the SRB technology.

The SRB bioreactors constructed at the Calliope abandoned mine site in the fall of 1998 are approximately 70 feet long, 14 feet wide, and 6 feet high. They are placed in parallel (see Figure 9) downstream from the pond, allowing the AMD to be piped to and treated in the reactors using

gravity flow. The bioreactors are designed to evaluate the SRB technology applied under different environmental conditions.

Two bioreactors are placed in trenches. One is constructed above the ground using a 12-foot-wide metal half-culvert to investigate the impact of seasonal freezing and thawing on SRB activity. To evaluate the efficiency of the SRB at optimal pH and oxidation-reduction potential (E_H), two of the reactors contain a passive pretreatment section to increase the alkalinity of the AMD.

Each reactor is filled with a combination of organic carbon and cobbles placed in discrete chambers (see Figures 9 and 10). Reactors II and IV also have a crushed limestone chamber. Each of these media is expected to play a certain role in the treatment train. 1) Organic carbon is the bacterial food supply, and because it was provided in the form of cow manure, also the SRB source. 2) For the pretreatment section, a chamber with cow

manure was included to lower the E_H of AMD. 3) Crushed limestone provided the buffering capacity to increase the pH of AMD in the pretreatment section. 4) Cobbles placed in the reactive, primary treatment section of the bioreactor constitute stable substrate for bacterial growth.

Chambers filled with organic carbon or limestone are each 5 feet long, whereas, chambers filled with cobbles are 50 feet long. Such dimensions were selected based on the literature review and information acquired through the bench-scale test that was conducted in the MSE Technology Applications, Inc., laboratory in 1998. Preliminary results of the bench-scale test, at the time of the bioreactor's design, indicated the required residence time in the reactors should range from 3 to 5 days. This resulted in the bioreactors being sized for a flow rate of one gallon per minute. To provide flexibility, the flow and hydraulic head control systems placed in the bioreactors ensure a much wider range of the residence time.

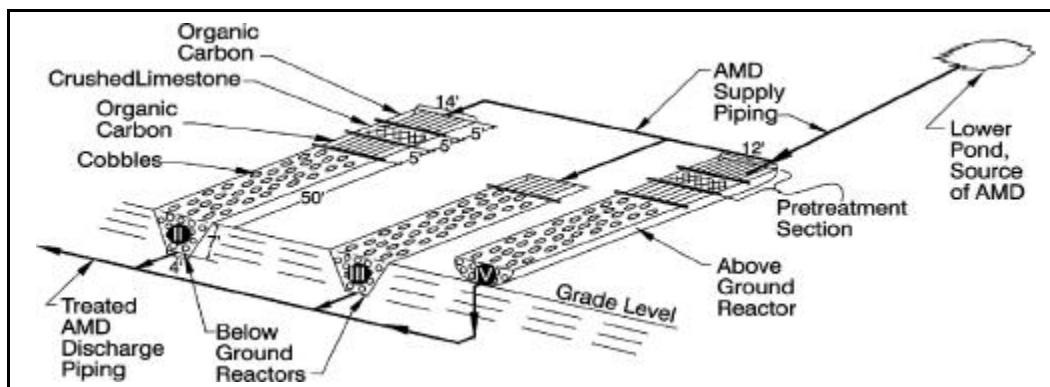


Figure 9. Layout of bioreactors.

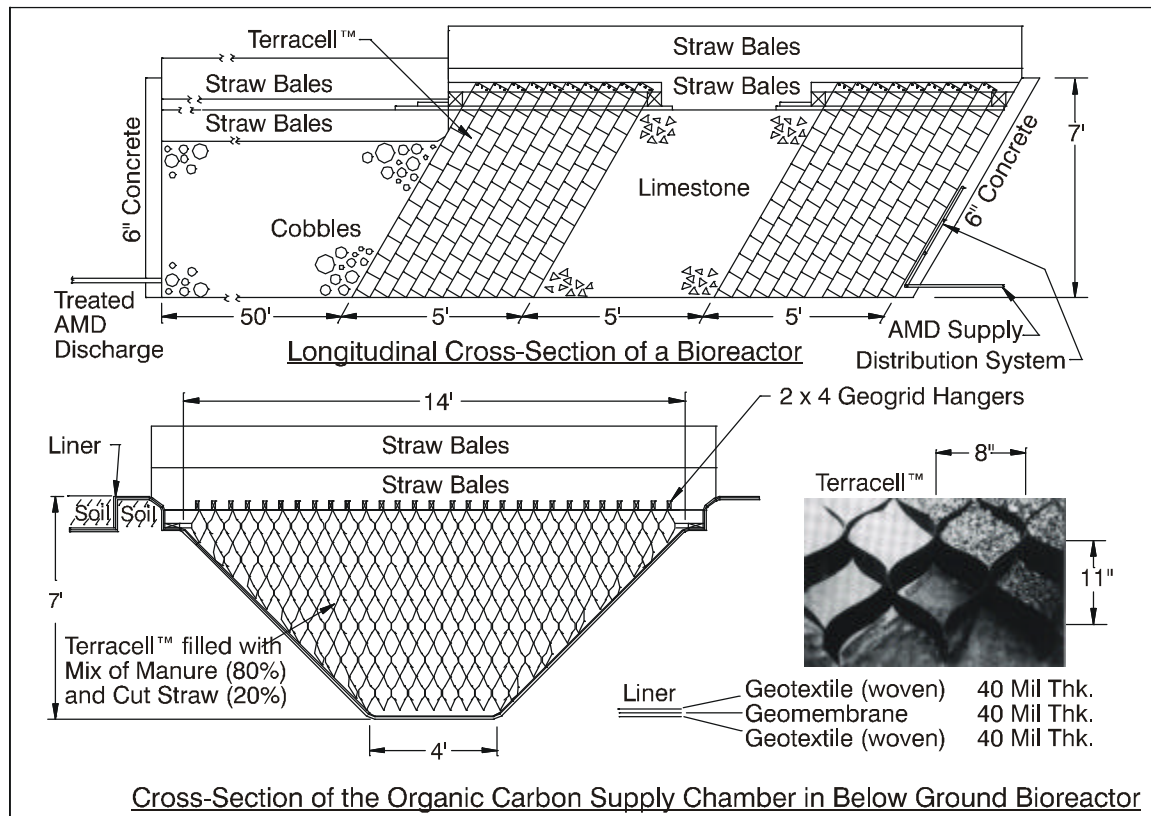


Figure 10. Bioreactor's design.

The main challenges were to design the organic carbon chambers so the AMD would permeate through the entire cross-sectional area without channeling and to ensure that the organic substrate did not settle. These goals were achieved by placing the organic substrate in the cellular containment system consisting of 10 lifts of Terracell™ (see geogrid in Figure 10) that would limit settling of the organic matter to each individual cell if it occurred. The Terracell™ lifts were positioned at 600 degrees off the horizontal plane to facilitate packing with the organic substrate and to promote migration of AMD along a wavy-shaped flowline.

Status

Reactor construction was completed in November 1998, and the reactors have been in operation since December 1998. The operation plan stipulated that the two below-grade reactors (II and III) would

flow at the rate of 1 gallon per minute (gpm) and reactor IV would be shut down for the winter to let it freeze full of AMD. After spring thawing, the flow rate of reactor IV would also be 1 gpm. The 1-gpm flow rate allows for approximately a 5½-day residence time of AMD in reactors II and IV and a 4½-day residence time in reactor III. The residence time of the AMD in a single organic carbon chamber was approximately 10 hours for the flow rate of 1 gpm.

Flow through Reactors III and IV has been maintained as desired for most of the time. The flow rate through Reactor II, however, started to decrease in May 1999 and ceased at the beginning of June. The flow rate was restored in July after the upgradient cell with organic carbon was chemically treated to remove biofouling and associated plugging. Similar behavior of Reactor II was observed again in May 2000. This time, the permeability of the upgradient chamber was

increased using an appropriate physical treatment. The repetitive plugging events of the most upgradient chamber in Reactor II seems to be attributed to a tighter packing of organic carbon in this chamber in comparison to other chambers.

The performance of each reactor has been monitored by monthly sampling of the influent (AMD) and effluent, and continuous monitoring of selected parameters using appropriate sensors and data loggers. Water samples have been analyzed for sulfate; alkalinity; SRB count; heterotrophic bacteria count; dissolved oxygen; E_H ; and metals that include aluminum, zinc, cadmium, copper, iron, manganese, and cadmium. Temperature, water level, and flow rate were recorded at 4-hour intervals by two data loggers. Selected results of the reactors performance are shown in Figures 11 through 14.

The first 8 months of operation can be described as a period in which the microbial populations were becoming established within the reactors. It should be noted that the reactors were started in the winter when temperatures were not ideal for microbial growth. As the reactor temperatures began to

increase in April 1999, an increase in SRB populations (Figure 11) was also seen. During the second winter of operation, the well-established SRB population was not affected by the low temperatures.

Much of the metals removal observed during the first 7 months of operation can be attributed to adsorption. Once sorption sites fill and SRB populations become established, many metals, like zinc and copper [(Figures 12 and 13 (logarithmic scale)] and cadmium (Figure 14), were removed from the AMD to threshold levels that were approximately 500 micrograms per liter ($\mu\text{g/L}$) to 800 $\mu\text{g/L}$ for zinc, 80 $\mu\text{g/L}$ for copper, and 5 $\mu\text{g/L}$ for cadmium. These removal levels were achieved despite the relatively low metals-concentrations in the influent AMD, caused by low atmospheric precipitation during the last 14 months of operation. For the metal concentrations present in the AMD at the Calliope site, the SRB population above 10^3 in one milliliter of the treated water was sufficiently high to maintain these removal levels. This means that the higher SRB population had no direct affect on the metal removal levels. This project will continue through the end of 2001.

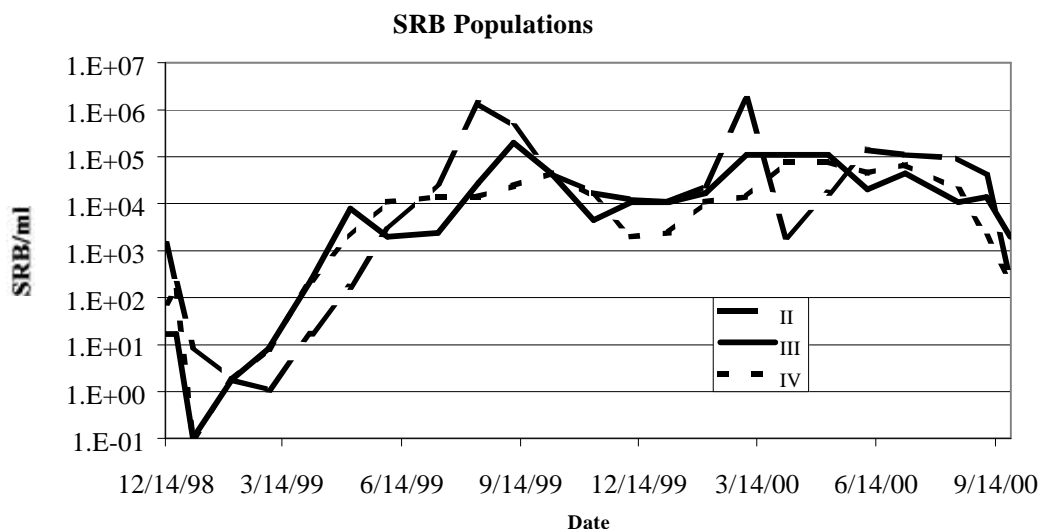


Figure 11. SRB populations.

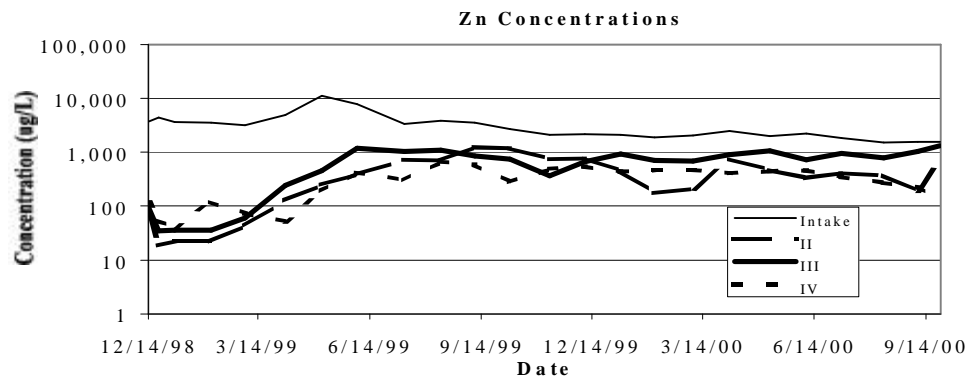


Figure 12. Concentration of zinc in AMD and reactor effluents.

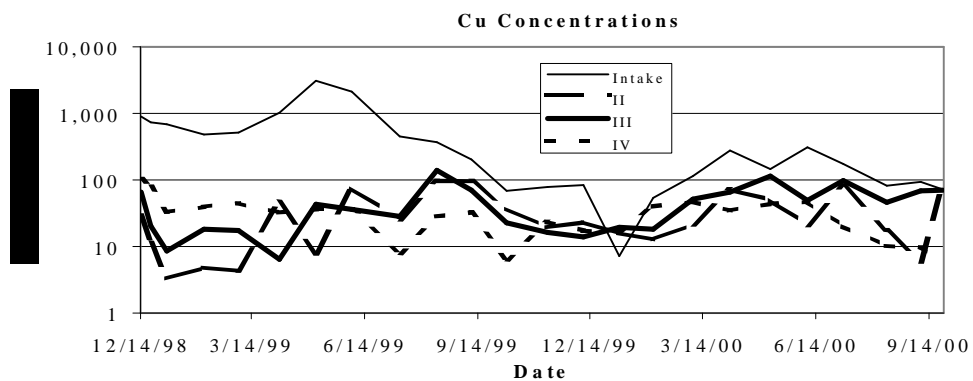


Figure 13. Concentration of copper in reactor effluents.

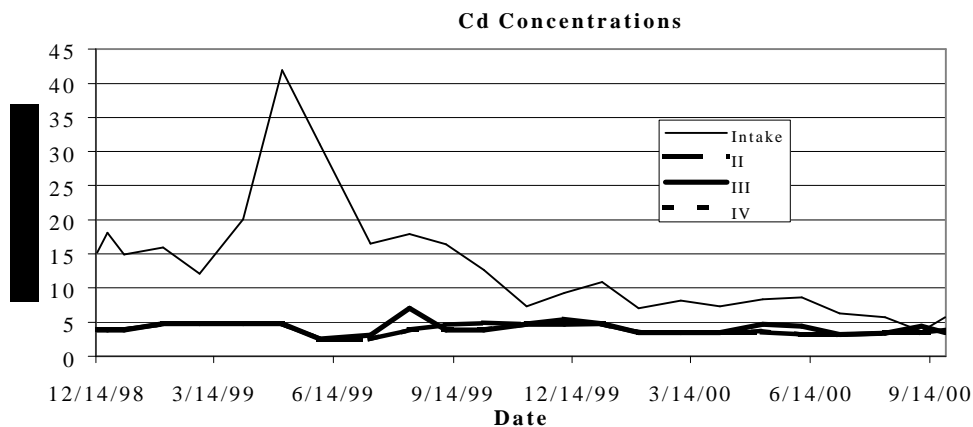


Figure 14. Concentration of cadmium in AMD and reactor effluents.

ACTIVITY III, PROJECT 12A CALLIOPE MINE INTERNET MONITORING SYSTEM

Project Overview

The technology addressed in this project is designed to poll and warehouse remote sampling data from the Calliope Mine site automatically. The remote monitoring is linked to the MSE Technology Application, Inc. (MSE) Testing Facility in Butte, Montana, via a cellular modem connection. Data from the remote site is polled by a dedicated personal computer (PC) located at the MSE Testing Facility. The project also includes technology to demonstrate remote site monitoring using two web cameras. The cameras download images to the PC at the MSE Testing Facility. The images and data can be viewed via the Internet from the dedicated PC.

Technology Description

The polling PC at the MSE site runs software designed for data loggers at the mine site. This software has the capability to poll data from the data loggers on a regular basis. Data is retrieved from the mine site only once a day since this is a solar-powered operation and more frequent retrieval would require a large battery bank. Once data has been retrieved, it is then transferred to an industrial database for warehousing. The polling PC is also connected to the World Wide Web via a dedicated 56-Kbs frame relay (see Figure 15).

Once data is stored it can be accessed from anywhere or any PC that has Internet capability. An Internet service provider was obtained to allow the connection as well as provide ample Internet protocol addresses and domain names for the web site. The web site domain name for this project is <http://www.environment-watch.com>. Figure 16 shows the web site home page.

The Web screens were designed to allow anyone with a PC and Internet access to view information from the telemetry system. The displays allow viewing of historical data as well as trending of data (see Figure 17).

Two remote cameras are connected to a small on site camera web server. The server is connected to the remote cellular modem just like the data loggers. The polling PC makes three calls to the mine site daily:

- one call in the morning to download site camera images of that morning;
- one call in the morning to retrieve data from the data loggers; and
- one call in the afternoon to download camera images of the site in the afternoon.

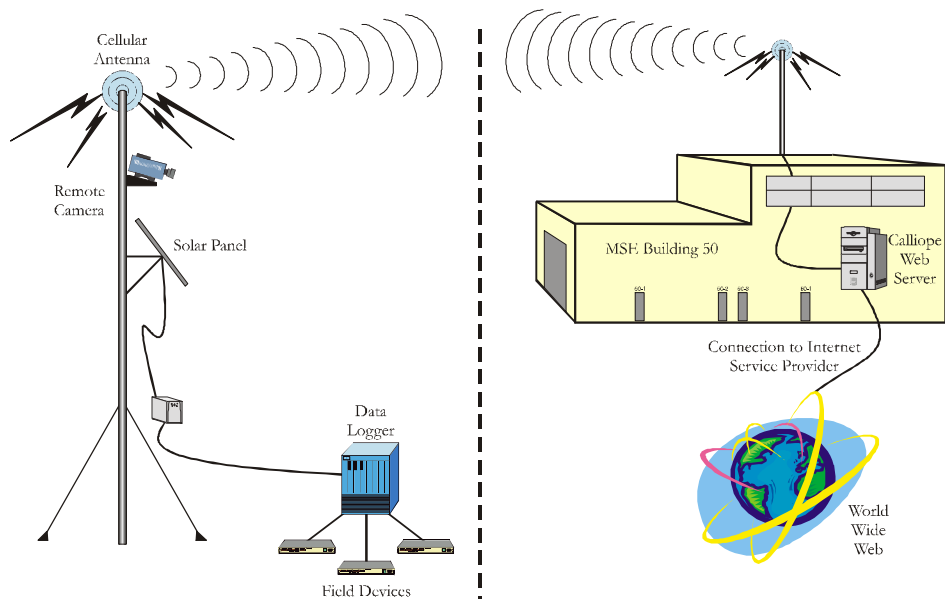
Once the data and the photos are downloaded, data is warehoused, and pictures are transferred to the web site for Internet viewing (see Figure 18).

This project also included the task of upgrading the existing data logger's battery storage capacity. The existing In-Situ Hermit 3000 Data Loggers did not have sufficient battery storage to run data loggers and existing instruments at specific sample rates. This problem was solved with the design of a new solar-powered battery charging system. The solar-charged batteries now power data loggers, instruments, the cellular telephone modem, web cameras, and web camera server.

This project installation has allowed additional capacity for future Mine Waste Technology Program projects. These projects can also benefit by using the same web server to post information onto the World Wide Web.

Status

As of September 30, 2000, the project was 100% installed and online. The project will remain open for maintenance and utility costs of the web server and other equipment. Maintenance is required for keeping the web server up to date as well as cover monthly cell phone and Internet service provider charges. This project will be closed out once the Calliope Mine site testing is completed. Possibly, another Mine Waste Technology Program project could pick up the monthly costs in the future.



At Calliope Mine Site
Figure 15. Calliope Mine Internet Monitoring System.

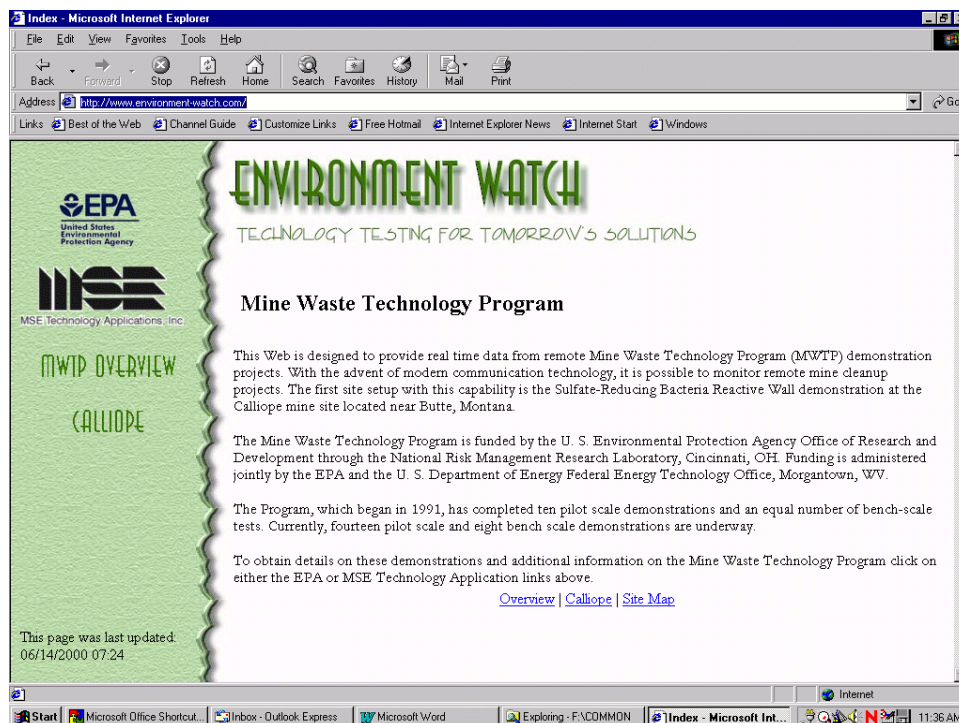


Figure 16. Environment-Watch.com home page.

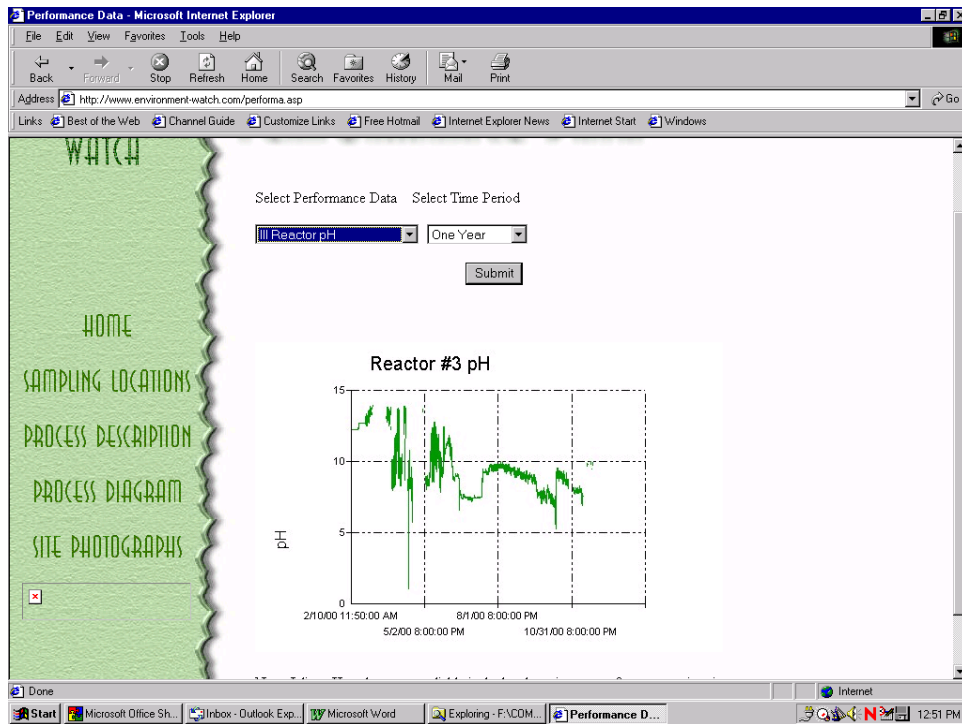


Figure 17. Historical trends screen for Calliope Mine data on the Environment-Watch.com web server.

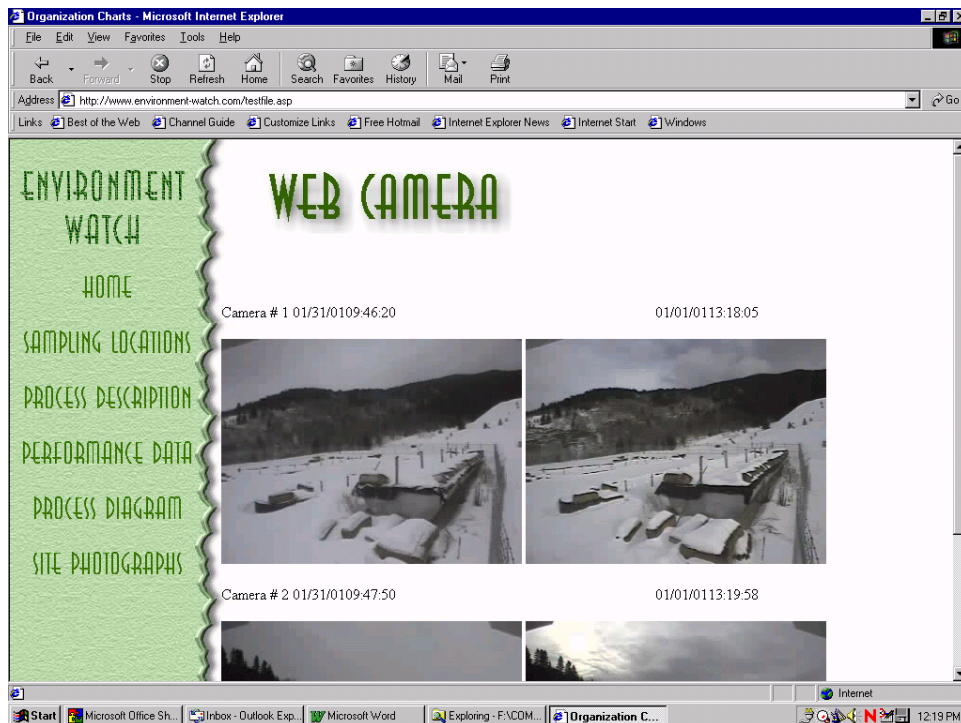


Figure 18. Web camera images displayed on web server twice daily.

ACTIVITY III, PROJECT 13: HYDROSTATIC BULKHEAD WITH SULFATE-REDUCING BACTERIA

Project Overview

The technology addressed in this project is designed to reduce or eliminate acid drainage from underground mine workings. The demonstration is intended to illustrate the feasibility of using an innovative source control technology in a way that provides increased stability, structural applicability and continuity, and economical comparability to the conventional methods of acid drainage treatment used by the mining and waste industries. The technology used for this demonstration will be stable in the environment.

Technology Description

The technology selected for this demonstration is a combination hydrostatic bulkhead constructed of concrete and rebar with a colony of sulfate-reducing bacteria (SRB) placed behind the bulkhead. The acid drainage in the mine will be treated by raising the pH of the contained water behind the bulkhead causing metals to be removed. The metals removal processes that can occur include adsorption and complexation of metals by organic substrates, biological sulfate reduction followed by precipitation of metals as sulfides, precipitation of ferric and manganese oxides, adsorption, adsorption of metals by ferric and manganese hydroxides, and filtration of suspended and colloidal materials. Biological sulfate reduction, however, should be the predominant metal removal mechanism.

Status

Preliminary design work was completed for installing a SRB colony behind a bulkhead to be constructed by the American Smelting and Refining Company at the Triumph Mine in Triumph, Idaho. U.S. Environmental Protection Agency (EPA) and MSE Technology Applications, Inc. (MSE) personnel reviewed the preliminary SRB design and agreed that this site was not a viable candidate for

installing a SRB colony due to the presence of extensive mine workings that would negate adequate treatment of waters inside the mine.

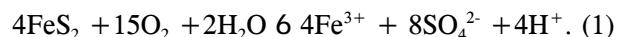
After eliminating the Triumph Mine as a demonstration site, the search was resumed for another site. It was decided by both EPA and MSE to suspend funding for this project effective fiscal 2001 after additional searching did not locate an appropriate site for this technology demonstration.

ACTIVITY III, PROJECT 14: BIOLOGICAL COVER DEMONSTRATION

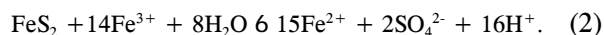
Project Overview

Acidic, metal-laden waters draining from abandoned mines have a significant environmental impact on surface and groundwater throughout the nation and the world. Specifically, the State of Montana has identified more than 20,000 abandoned mine sites, on both public and private lands, resulting in more than 1,300 miles of streams experiencing pollution problems.

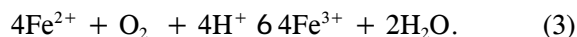
Acid mine drainage arises from tailings and waste rock containing sulfide minerals and lacking acid-consuming carbonate minerals. Sulfide minerals, such as pyrite (FeS_2), are oxidized to form sulfate when water containing oxygen infiltrates tailings and waste rock. This process can be described by the following reaction:



The activity of bacteria, such as *Thiobacillus ferrooxidans*, which are capable of oxidizing inorganic sulfur compounds, greatly accelerates this reaction. The ferric iron (Fe^{3+}) produced in the above reaction also contributes to pyrite oxidation:



T. ferrooxidans is also capable of oxidizing ferrous iron (Fe^{2+}) produced in the above reaction:



Although the above reaction consumes some acidity, the ferric iron produced is capable of oxidizing more pyrite and producing much more acidity (via reaction 2).

The key to breaking this cycle is preventing the initial oxidation of pyrite. Bound with iron, the sulfur in pyrite is unable to participate in the microbially catalyzed reactions that cause acid generation. Preventing oxygen infiltration into tailings and waste rock is necessary to prevent oxidation of pyrite and subsequent acid generation. An innovative method to prevent oxygen transport into tailings is constructing and maintaining a biologically active barrier on the surface of the tailings. This barrier is made up of microorganisms that consume dissolved oxygen from the infiltrating water, thereby, maintaining the reducing conditions necessary for pyrite to remain bound in mineral form.

MSE Technology Applications, Inc. and researchers at the Center for Biofilm Engineering at Montana State University are investigating the microbial processes involved with establishing and maintaining subsurface and near surface microbial barriers for hydraulic control and microbially catalyzed reactions. Biofilm barrier technology has been successfully tested in laboratory and field-scale systems where permeability reductions of five orders of magnitude were achieved. During these tests, it was also shown that biofilm barriers can successfully remove oxygen from infiltrating waters to trace levels.

By conducting this demonstration, the Mine Waste Technology Program is illustrating the ability of microbial biomass to reduce the permeability of mine tailings and remove oxygen from infiltrating water, thereby, reducing the generation of acid mine drainage. This technology promises to be a cost-effective approach for stabilizing and remediating acid-generating abandoned mine tailings.

Technology Description

A biologically active zone is established in the tailings by adding a nutrient solution to the surface of the tailings pile. The nutrient solution contains low cost ingredients that serve as sources of carbon

and energy for microbial growth, as well as sources of nitrogen, phosphorous, and necessary micronutrients. The nutrient solution is formulated to stimulate indigenous oxygen-consuming microorganisms, as well as sulfate-reducing bacteria (SRB). In some cases, a microbial inoculum containing appropriate microorganisms may have to be added. The oxidation of carbon compounds in the nutrient mixture by microorganisms depletes oxygen from infiltrating water. Also, bacterial cells and associated extracellular polymers occupy free pore space within the tailings matrix, greatly reducing permeability. The reduction of water volume flowing through the tailings and depletion of oxygen as water passes through the barrier will mitigate pyrite oxidation and subsequent acid generation. The anaerobic conditions and production of organic acids by fermentative bacteria will also promote SRB growth. The SRB activity is desirable because it neutralizes acid and stabilizes metals by H_2S -mediated metal sulfide precipitation. After establishing the biological barrier, periodic nutrient treatments are applied to maintain the barrier.

Status

The Mammoth tailings site in the South Boulder Mining District, approximately 18 miles from Cardwell, Montana, was selected for implementing this technology. Two, lined test cells were constructed at the field site in the fall of 1999. An initial nutrient treatment was applied to one of the test cells (treated cell) in the fall of 1999. Additional nutrient treatments were applied to the treatment cell in May, June, and August 2000. The nutrient formulation included molasses as a carbon and energy source, urea as a source of nitrogen, and potassium phosphate. The control (untreated) cell received an equivalent amount of water to that applied to the treatment cell during nutrient treatments. Other than the four nutrient or water treatments, all water entering the test cells was due to natural precipitation. The test cells were not operated during the winter months when they were frozen.

Drainage from the treatment cell had a slightly higher pH and slightly lower oxidation reduction potential than the control cell. The mean pH of drainage from the test and control cells were 6.4

and 6.2, respectively. Microbiological analysis indicated higher populations of total bacteria, general heterotrophic bacteria, and sulfate-reducing bacteria in drainage from the treated cell, relative to the control cell. Populations of sulfur-oxidizing bacteria (e.g., *Thiobacillus ferrooxidans*) were similar in drainage from both test cells. Dissolved sulfate concentrations were lower in drainage from the treated cell, while total organic carbon concentrations were higher. Drainage from the treated cell had lower concentrations of dissolved aluminum, copper, and zinc and higher concentrations of iron and manganese than the control cell. Overall, these results indicate that treatment with a carbohydrate- (molasses) based nutrient formulation had a mild effect on the biological and chemical processes occurring in the tailings and led to a slight improvement in the water quality of drainage from the tailings. Laboratory column tests (described below) have indicated that protein- (whey) based nutrient formulation was more effective than the carbohydrate-based treatment for mitigating acid mine drainage. During the 2001 field season, a protein- (whey) based nutrient formulation will be applied to the treatment cell.

Laboratory experiments performed at the Center for Biofilm Engineering at Montana State University have included packed-column tests using tailings from the Mammoth Field Site, Crescent Mine (Montana), and the Fox Lake Mine (Manitoba, Canada). The columns packed with tailings from the Crescent Mine failed to generate acidity or significant concentrations of dissolved metals. Treatment of these columns with the carbohydrate-based nutrient treatment did result in a significant decrease in oxidation-reduction potential (ORP) relative to a control column.

Three columns were packed with tailings from the Fox Lake site, and two of these received the carbohydrate-based nutrient treatment, while the third column served as an untreated control. One of the treated columns responded with a significant increase in pH and reduction in ORP, as well a decrease in dissolved aluminum and zinc concentrations. However, the other treated column responded with a decrease in pH and an increase in ORP. It is hypothesized that the carbohydrate-based nutrient treatment to this column resulted in the proliferation of acid-generating fungi. This hypothesis is being investigated further at the Center for Biofilm Engineering. Due to the lack of consistent laboratory results and marginal field success with the carbohydrate-based nutrient formulation, a protein-based nutrient formulation using whey (a by-product of cheese manufacturing) was applied to columns packed with tailings from the mammoth site. The whey treatments resulted in a significant increase in the pH and a decrease in the ORP of drainage from the tailings (see Figure 19). This effect was more dramatic and longer lasting than the molasses treatments performed previously. The use of whey-based nutrient treatments is currently being further evaluated in the laboratory.

Overall, results of laboratory and field testing indicate that biological cover technology is feasible for source control of acid mine drainage. However, the results suggest that correct nutrient formulation is critical to the success of the treatment; and in some cases, adding an inappropriate nutrient formulation can decrease the water quality of drainage from mine tailings. Further research is necessary to define the critical parameters for formulating a nutrient mixture for treating a specific mine site.

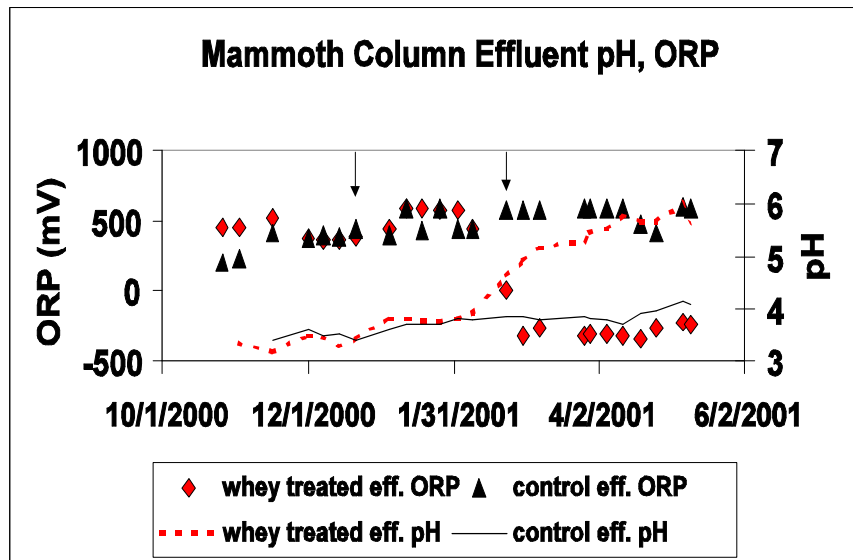


Figure 19. pH and ORP in effluent from laboratory columns packed with tailings from the Mammoth Site. The arrows indicate treatment of the test column with a nutrient solution containing whey as a carbon and energy source for microbial growth. After a lag period, which represents the hydraulic residence time of the column, a significant increase in pH and a decrease in ORP were observed in effluent from the treated column. This effect was not observed in the untreated control column.

ACTIVITY III, PROJECT 15: TAILINGS SOURCE CONTROL

Project Overview

Processing metallic ores to extract the valuable minerals leaves remnant material behind called tailings. In the case of sulfide mineral-bearing ores, process tailings often contain large quantities of sulfide minerals that do not meet the economic criteria for extraction. These remnant sulfide minerals are usually pyrites and nonextracted ore minerals. The exposure of these minerals to air and water often leads to detrimental environmental conditions such as increased sedimentation in surface waters due to runoff events, increased wind borne particulate transport, generation of acid mine drainage, and increased metals loading in surface and ground waters.

Technology Description

The objective of this demonstration was to identify potential source control materials and apply one or more of them at a selected site. The demonstration consists of two phases: 1) site characterization and materials testing; and 2) materials emplacement and long-term monitoring and evaluation.

Phase one consisted of the site characterization studies, including hydrogeological, geological, and geochemical information directly related to the tailings impoundment. The materials testing and development involved testing, evaluation, and formulation of source control materials for application at the selected site.

Phase two will encompass the application of one or more of the selected source control materials at the demonstration site and an evaluation of the material

application and feasibility. Long-term evaluation of the materials will be performed using air borne particulate tests, moisture profiles generated from monitoring equipment, and post-application material tests.

Status

For Phase one, the project site selected for this demonstration is the Mammoth Tailings site located adjacent to the historic mining town of Mammoth,

Montana (see Figure 20). Material testing was finalized during the first quarter of 2000. Three source control materials are scheduled to be applied at the Mammoth Tailing site, which include two, polymeric cementitious grouts that incorporate the tailings material as a filler material and a spray-applied, modified chemical grout. Due to forest fire restrictions, the emplacement of the source control materials was postponed from 2000 to the summer of 2001. The project will be completed by the end of calendar year 2001.



Figure 20. Mammoth Mine Tailings site.

ACTIVITY III, PROJECT 16: INTEGRATED PASSIVE BIOLOGICAL TREATMENT PROCESS DEMONSTRATION

Project Overview

The objective of this project is to develop technical information on the ability of an integrated passive biological reactor to treat and improve water

quality at a remote mine site. This technology offers advantages over many acid mine drainage (AMD) treatment systems because it does not require a power source or frequent operator attention. For this demonstration, the technology will treat the acidic aqueous waste by removing toxic, dissolved metallic and anionic constituents from the water in situ and increasing the pH so the effluent is near neutral.

Technology Description

The technology uses a series of biological processes for the complete mitigation of AMD by concentrating and immobilizing metals within the reactors and raising the pH of the water. Both anaerobic and aerobic bacteria will be used. The bacteria will be fed inexpensive waste products such as feed-lot wastes. The anaerobic bacteria, sulfate-reducing bacteria (SRB), are a group of common bacteria that are able to neutralize AMD and remove toxic metals. When supplied with sulfate (present in mine water) and a carbon source, SRB produce bicarbonate and hydrogen sulfide gas. Bicarbonate neutralizes AMD while hydrogen sulfide gas reacts with metal ions to precipitate them as insoluble metal sulfides. Aerobic bacteria will be used to mitigate metals, such as iron and manganese, that are not removed satisfactorily by SRB. The result will be an integrated biological system capable of completely and passively mitigating AMD. The field system is depicted in Figure 21.

The first phase of the project will include field site selection and characterization and laboratory testing. Laboratory testing will be performed to identify design parameters for the field design.

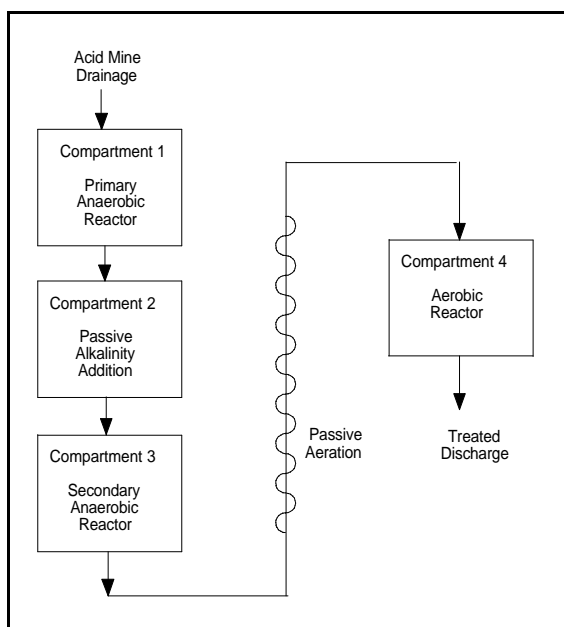


Figure 21. Field system for Integrated Passive Biological Treatment Process Demonstration

The second phase of the project will include the design and construction of an integrated passive biological treatment system to treat AMD at the selected remote mine site, the Sure Thing Mine located in Southwest Montana.

Status

The design of the field-scale system was completed in fiscal 2000. Construction was scheduled during the summer of 2000 but was postponed because wild fires caused National Forest closures. Construction is now scheduled for the summer of 2001.

ACTIVITY III, PROJECT 19: SITE IN SITU MERCURY STABILIZATION TECHNOLOGIES

Project Overview

This demonstration project is being conducted in conjunction with the U.S. Environmental Protection Agency's Superfund Innovative Technology Evaluation Demonstration Program. Mercury contamination often is a critical problem at mine sites, and there is a recognized need to identify technologies for mercury remediation. The application of an in situ mercury stabilization technology would provide an alternative treatment to completely removing mercury-contaminated materials from remote abandoned mine sites. As part of the overall project, MSE Technology Applications, Inc. (MSE) is responsible for conducting technology assessment activities to comparative mercury stabilization tests using mercury-contaminated material.

The Sulphur Bank Mine in Clear Lake, California, was chosen as the source of mercury contaminated mining wastes for this demonstration project. This abandoned mine, located in a geothermal active area, was historically mined for mercury and sulfur. It is now part of a 120-acre superfund site containing tailings, rock piles, and a pit lake. The mine tailings are located upgradient and extend into and along the shoreline of Clear Lake. The development of an in situ mercury

treatment/stabilization technology could be used to address the significant mercury contamination problems at the site.

Technology Description

The main objective of this effort is to determine a suitable method for in situ mercury stabilization. This technology demonstration project will help to show the effectiveness of various technologies for the in situ treatment/stabilization of mercury contaminated mining materials. Several applicable technologies will be identified and tested. These may include chemical precipitation, micro-encapsulation, and grouting.

Status

MSE is conducting a series of comparative column treatability tests of various mercury treatment/stabilization technologies. The technologies were selected with regards to their ability to reduce the leaching, mobility, and toxicity of mercury contamination. Two materials from the Sulphur Bank Mine site have been selected for testing. The effectiveness of the treatment technologies will be evaluated by performing post-treatment kinetic column leach tests. The immobilization of mercury over time and the reduction of leachable mercury relative to untreated controls will be determined. The information gained from this project will serve to provide data for abandoned mine remediation projects.

ACTIVITY III, PROJECT 20: SELENIUM REMOVAL/TREATMENT ALTERNATIVES

Project Overview

The purpose of the Selenium Removal/Treatment Alternatives Demonstration Project is to: 1) evaluate the performance of the selected processes in the field using selenium-bearing water; 2) evaluate the affect of competing ions on

selenium removal efficiency; and 3) determine full-scale capital and operating costs of the processes being demonstrated.

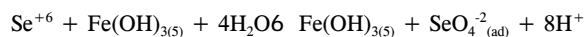
The following selenium removal technologies have been demonstrated at field-scale: 1) U.S. Environmental Protection Agency's (EPA) Best Demonstrated Available Technology (BDAT) for treating selenium-bearing waters and coprecipitation of selenium using ferrihydrite as optimized by MSE Technology Applications, Inc. (MSE); 2) catalyzed cementation technology developed by MSE; and 3) biological reduction of selenium technology developed by Applied Biosciences Corporation of Park City, Utah. An enzymatic reduction of selenium technology also developed by Applied Biosciences Corporation of Park City, Utah, was demonstrated on a bench-scale.

The field demonstrations were conducted at Kennecott Utah Copper Corporation. The influent water used for the demonstration was a ground water containing approximately 2 ppm selenium. The primary objective was to reduce the concentration of dissolved selenium in the effluent waters to a level under the National Primary Drinking Water Regulation Limit for selenium of 50 ppb established by EPA.

Technology Description

Ferrihydrite Precipitation

Ferrihydrite precipitation with concurrent adsorption of selenium onto the ferrihydrite surface is the BDAT for treating selenium-bearing waters. For the coprecipitation to occur, ferric ion (Fe^{+3}) must be present in the water. Selenate (Se^{+6}) is removed from the water at pH below 4. The chemical reaction for ferrihydrite precipitation of selenium is:



The ferrihydrite precipitation process is shown in Figure 22.

Catalyzed Cementation of Selenium

Catalyzed cementation has been developed to remove arsenic and other heavy metals such as

thallium and selenium from water. The term catalyzed cementation describes the process's ability to remove contaminants from solution by cementation (adsorption) onto the iron surface. It is anticipated that the catalyzed cementation process will have the ability to treat and remove selenium from solution regardless of its valence state (+6 or +4). To optimize the cementation process, proprietary catalysts are added to increase the removal efficiency of the process. This process has been shown in similar tests to reduce selenium concentrations below the Maximum Contaminant Level of 50 ppb. The catalyzed cementation process is shown in Figure 23.

Biological Reduction of Selenium

To accomplish biological selenium reduction, researchers at Applied Biosciences of Salt Lake City, Utah, have developed a process using baffled anaerobic solids bed reactors (BASBR). The process is depicted in Figure 24. Selenium (selenate and selenite) will be reduced to elemental selenium by specially developed biofilms containing specific proprietary microorganisms. This produces a fine precipitate of elemental selenium. The marketability of the elemental selenium product will be investigated during this project. This process is being demonstrated using equipment designed and constructed by ABC with assistance from Kennecott Utah Copper Corporation.

The pilot-scale BASBR will be used to investigate the feasibility of using a defined mixture of *Pseudomonas* and other microbes for removing selenium from influent water.

Enzymatic Reduction of Selenium

Applied Biosciences also demonstrated, at bench scale, a proprietary enzyme technology for selenium removal. This metal reducing technology is based on proprietary enzyme extraction/purification methods combined with

unique immobilization/encapsulation techniques that keep the selenium reducing enzyme(s) in a functional arrangement within an immobilized/encapsulated matrix. The adaptation, enhancement, and use of microbial components, and byproducts (proteins, enzymes, and polymers) show considerable promise for treatment/removal of metals and other inorganics in complex wastewaters. Normal biofilms developed for selenium reduction and removal can be quickly overgrown as the bioreactor system is exposed to waste and process waters containing indigenous microbes and nutrients. Overgrowth of the selenium-reducing population in a bioreactor can be delayed by optimizing the bioreactor and nutrient selection for the chosen selenium reducer. However, once nutrients are added, time and indigenous microbes slowly erode the selenium reducing capability. This situation can be avoided by using selenium-reducing enzyme preparations.

Status

The field demonstration of the BDAT technology, catalyzed cementation, and biological reduction technology was completed. All three technologies removed selenium to below the project objective of 50 ppb under optimum conditions. The biological reduction technology was the most consistent process tested, with the majority of results less than the detection limit for selenium of 2 ppb. An interim report is being drafted and will be submitted to EPA for review in November 2000.

The laboratory demonstration of the enzymatic selenium reduction technology was completed. Although selenium reducing enzymes were isolated, the unstable nature of them prevented a pilot-scale demonstration of this technology. Applied Biosciences is preparing a report about the laboratory study that will be included in the final project report. The final report will be submitted to EPA for review in April 2001. Project closeout is scheduled for June 2001.

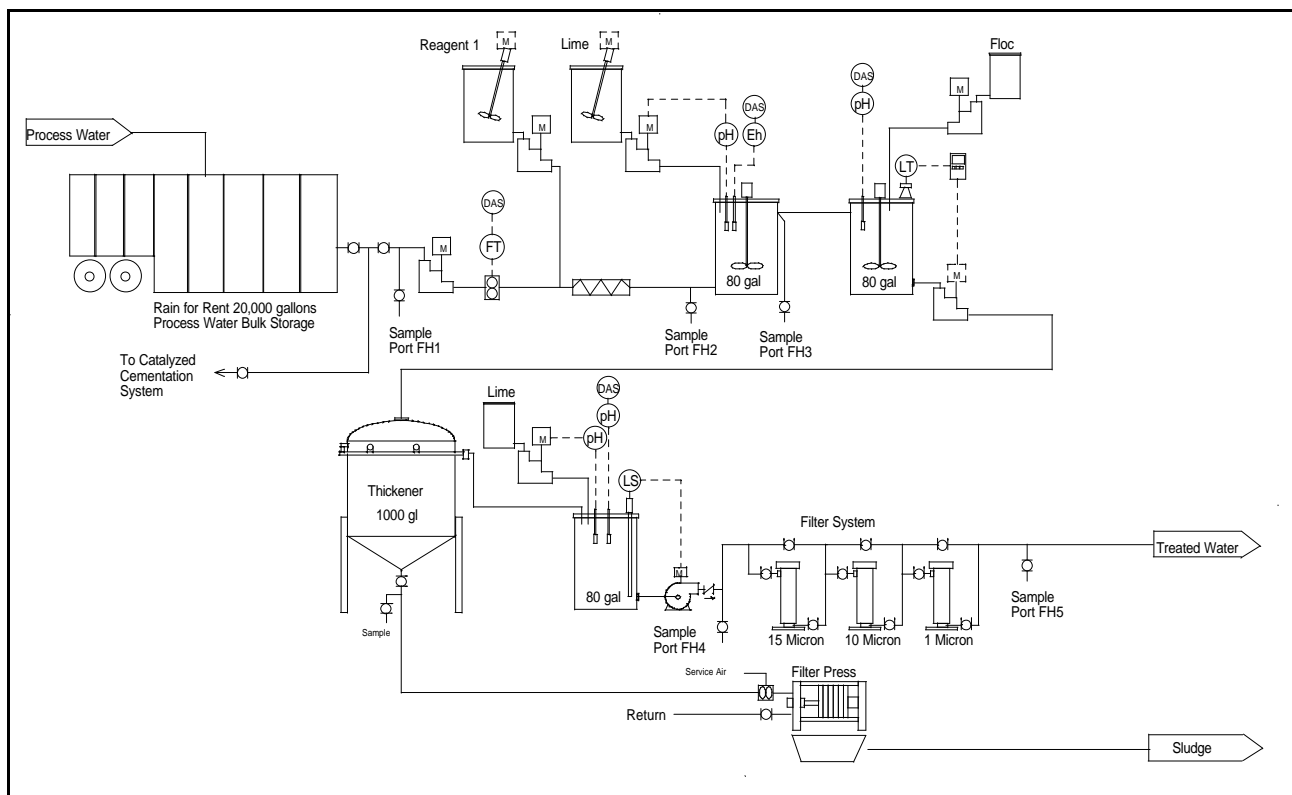


Figure 22. Ferrihydrite precipitation process flow diagram.

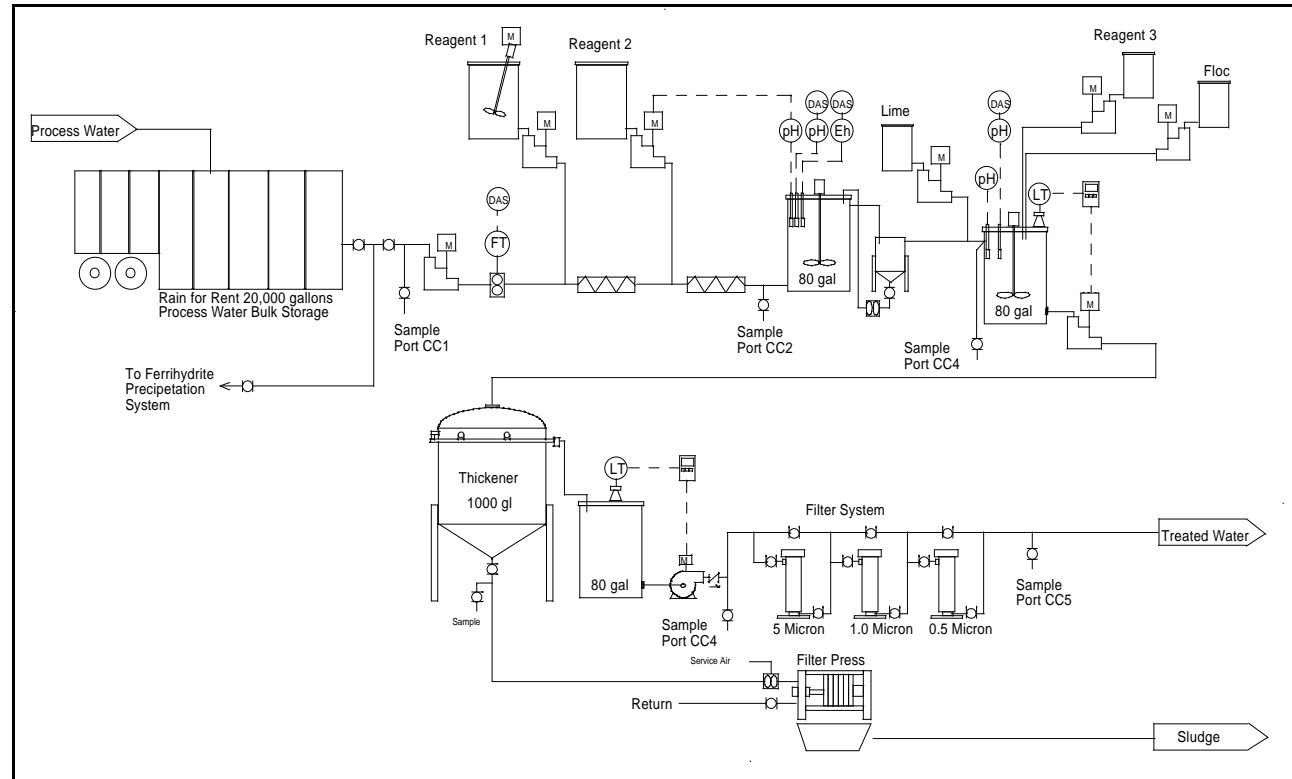


Figure 23. Catalyzed cementation process flow diagram.

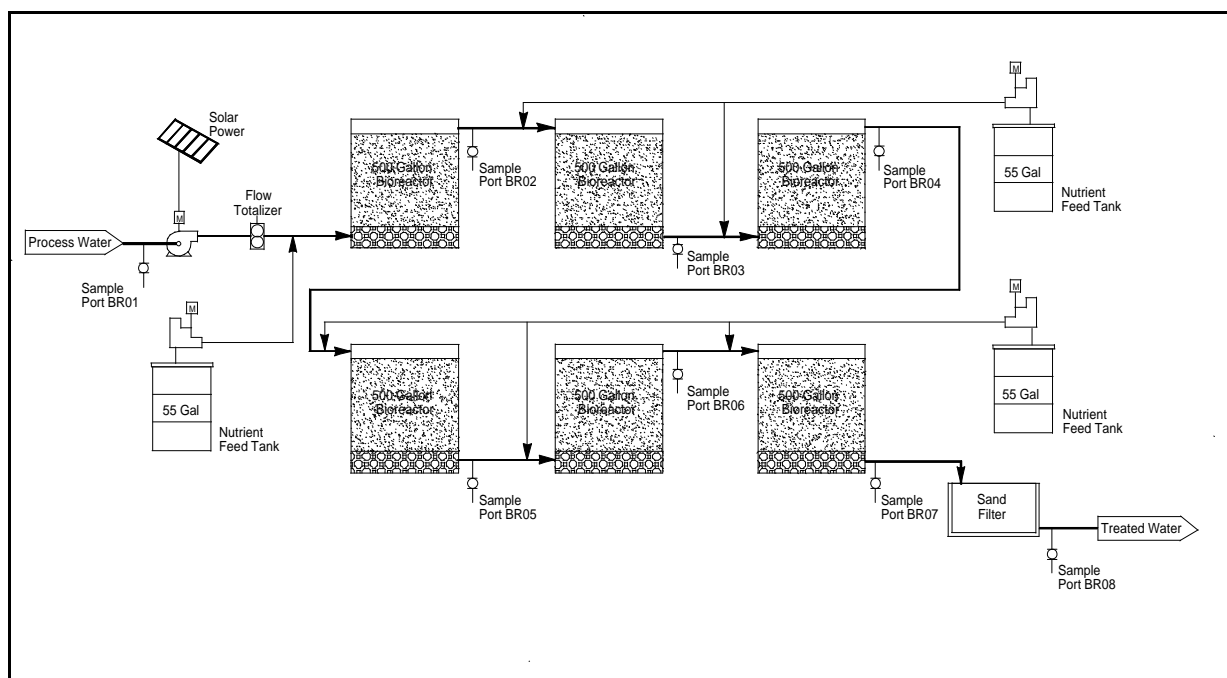


Figure 24. Biological selenium reduction process flow diagram.

ACTIVITY III, PROJECT 21: INTEGRATED PROCESS FOR TREATMENT OF BERKELEY PIT WATER

Project Overview

The objective of this project is to develop integrated, optimized treatment systems for processing Berkeley Pit water. The Berkeley Pit is an inactive open-pit copper mine located in Butte, Montana. Currently containing approximately 30 billion gallons of acidic, metals-laden water, the Berkeley Pit is filling at a rate of approximately 3 million gallons per day and is a good example of acid rock drainage.

Two optimized flow sheets will be developed for this project. One flow sheet is to be oriented toward minimizing the overall cost of water treatment to meet discharge requirements—this will include not only water treatment equipment but also sludge handling/management. The other flow sheet is to be oriented toward also meeting discharge

requirements but includes the recovery of products from the water (copper, metal sulfates, etc.) to potentially offset treatment costs and result in overall better economics.

Technology Description

The project will evaluate proven technologies as well as technologies with credible pilot-scale supporting data. Technologies with only laboratory testing history will not be included, which would include technologies for sludge management, solid/liquid separation, dewatering, drying, etc., as well as technologies for product recovery from water. The goal is to assemble the sequence of unit operations resulting in the most attractive overall economics.

Status

A uniform cost estimating approach was developed and documented to ensure that consistent assumptions and uniform approaches are used for all scenarios evaluated. A conceptual design of a

filter cake repository was completed. This was important because a repository location had only recently been established, allowing reasonable cost estimates to be prepared for the first time. Two flow sheets were identified to be used as baseline references with which to compare possible improvements. An extensive verification effort was performed to place both reference flow sheets on the same design basis and perform cost estimates and economic analyses consistent with the approach mentioned above. This verification effort included technical verification as well as economic verification. A result of the verification effort was that sludge dewatering was found to be extremely expensive; since discharge of sludges to the Berkeley Pit is an option requiring study before approval, a small-scale test program was conducted to evaluate the effects of returning settled sludges to the Berkeley Pit for a 30-year period. Another significant result of the verification effort was that the cost of using a strong oxidant for iron oxidation and removal prior to recovery of other metals was exorbitant; therefore, other methods for iron oxidation at low pH were investigated. The most promising was found to be Inco's sulfur dioxide/air process used to oxidize cyanide, which was investigated at bench scale by Inco with very encouraging results. Various trade studies were performed, for example, evaluating a high-density sludge system versus a conventional precipitation system. An evaluation was performed to evaluate the feasibility of on-site upgrading of raw products to increase their marketability and value. For example, a metal recovered as a carbonate could be calcined to an oxide, thereby, increasing its grade and reducing shipping costs.

ACTIVITY III, PROJECT 22: PHOSPHATE STABILIZATION OF MINE WASTE CONTAMINATED SOILS

Project Overview

The project goal is to provide information to support technical feasibility and regulatory acceptance of phosphoric acid-based in situ

stabilization of lead in residential soils at the Joplin, Missouri National Priorities List Site. The ultimate goal is to demonstrate this technique is a cost-effective alternative to excavation and haulage of metal-contaminated soils to a waste repository.

Technology Description

The remediation approach involves mixing commercial grade phosphoric acid and a trace of potassium chloride into near surface soils, followed by pH adjustment (e.g., with lime addition) to attain paraneutrality. As a result, soluble lead is converted to pyromorphite, a highly insoluble and environmentally stable mineral. Subsequently, lead uptake from rooting zone soils (into aboveground plant biomass) and into the bloodstream of young children (from the gastrointestinal tract) is significantly reduced.

Status

The following project planning documents were completed in fiscal 2000: Work Plan; Quality Assurance Project Plan; NEPA Compliance/Site Access Agreement; and a Health and Safety Plan. The subcontract with the Missouri Department of Natural Resources (MDNR), Hazardous Waste Division, for field and document preparation support was completed. The subcontract with the University of Missouri's Veterinary Medical Diagnostic Laboratory for soils characterization and pig dosing studies was nearly completed. The U.S. Environmental Protection Agency (EPA)/Las Vegas' Environmental Monitoring Laboratory agreed to perform in vitro assessments of lead bioaccessibility, as requested by EPA Region 7 and funded by EPA's Office of Solid Waste and Emergency Response. MDNR personnel began to mobilize for the field treatment work in mid-September 2000.

ACTIVITY III, PROJECT 23: REVEGETATION OF MINING WASTE USING ORGANIC AMENDMENTS AND EVALUATE THE POTENTIAL FOR CREATING ATTRACTIVE NUISANCES FOR WILDLIFE

Project Overview

The objectives of this project are to demonstrate the use of organic amendments to enhance the establishment and growth of grass on lead mine tailings and to evaluate the affect of those amendments on plant uptake of metals. Two sources of compost and an organic fertilizer derived from municipal sewage treatment plant sludge were incorporated into two types of tailings near Desloge, Missouri, and the replicated plots were planted with grass. Both types of tailings (fine-textured floatation tailings and course-textured gravity separation tailings referred to as chat tailings) contain elevated concentrations of lead, zinc, and cadmium. This project will be evaluated for three growing seasons.

Thousands of abandoned mine and mineral processing sites throughout the United States are very unattractive and can be a significant environmental hazard. The federal government and responsible parties need to develop cost-effective remedial approaches to effectively manage these large areas that are contaminated with a wide variety of metals. Natural revegetation is often prevented in these areas because of low pH, phytotoxic concentrations of metals, poor physical structure for plant growth, nutrient deficiencies, and slopes too steep for plant establishment. Mine waste reclamation research frequently includes the addition of organic soil amendments, since mine waste materials are typically subsurface in origin and have minimal organic content. However, the diversity of organic amendments used and the lack of uniformity within each category of material make comparisons among sites and studies difficult. In addition, while it is generally agreed that organic amendments are capable of stabilizing mine waste metals, the potential for post reclamation impacts to wildlife

due to plant uptake of those metals requires further research.

Technology Description

MSE Technology Applications, Inc., established field plots at the Big River Mine Tailings Site and the Leadwood Chat Tailings Site in Missouri in the spring of 2000. The plots were evaluated to determine vegetation establishment, biomass production, and plant uptake of metals. Procedures for establishing, maintaining, and evaluating the plots will be broadly applicable and reproducible so that subsequent studies at other locations will produce comparable information. The three organic amendments are milorganite, ormiorganics compost, and St. Peters compost. These amendments were applied at a low, medium, and high application rate. Each amendment/application rate combination was replicated four times including a control plot that only received the inorganic fertilizer at both sites, totaling 80 plots. The plant species for the demonstration was tall fescue (Kentucky variety). The plots were monitored monthly from May through September 2000. The project will be evaluated for three growing seasons.

Status

Figure 25 shows the Leadwood Chat Tailings site prior to planting, and Figure 26 shows the site after incorporating the organic amendments and 7 months of growth. Figure 27 shows the Big River Mine Tailings site prior to planting, and Figure 28 shows the site after incorporating the organic amendments. At the end of the first growing season, vegetative cover and biomass production were quantified, and tailings and vegetation samples were obtained and analyzed. Preliminary results indicate the amendments improve both establishment and growth, differences among amendment types and application rates are significant, and plant uptake to metals is not great enough to impact area wildlife. Additional results of the first growing season will be discussed in an Interim Report to be issued in March 2001. Project completion is expected in December 2002.



Figure 25. Leadwood Chat Tailings site prior to planting.



Figure 26. Leadwood Chat Tailings site after incorporating the organic amendments.



Figure 27. Big River Mine Tailings site prior to planting.



Figure 28. Big River Mine Tailings site after incorporating the organic amendments.

ACTIVITY III, PROJECT 24 IMPROVEMENTS IN ENGINEERED BIOREMEDIATION OF ACID MINE DRAINAGE

Project Overview

Acid mine drainage (AMD) emanates from many abandoned mine sites in the western United States. Such drainage, having an elevated content of dissolved metals and low pH, presents an environmental problem that needs to be economically addressed. Sulfate-reducing bacteria (SRB) have the ability to immobilize dissolved metals, by precipitating them as sulfides, and increase pH provided that a favorable biochemical environment is created. Such conditions may be created by constructing artificial wetlands, if space is not limited, or converging the AMD flow to an engineered passive SRB reactor.

A SRB reactor contains an organic-carbon chamber that is vital for its operation. A life span of a properly designed reactor depends on the organic carbon supply, permeability of organic-carbon chamber, and the capacity of the reactor to accumulate precipitated sulfides.

When the source of organic carbon is depleted, or becomes unavailable, because permeability of the organic matter decreased due to settling processes or physical or chemical encapsulation, the bioreactor will cease operating. To reactivate such a bioreactor, the organic carbon source has to be either replenished or rejuvenated. Therefore, it is desirable to: 1) maximize the time interval between such operations; and/or 2) be able to predict the longevity of the carbon source to economically optimize the reactor's size.

Similarly, when the capacity of the bioreactor's chamber that was designed to hold precipitated sulfides is exhausted, the sulfides will either break through or the reactor will plug ceasing its operation.

This project addresses engineering improvements that include replacing the organic carbon supply-system in a SRB reactor and refining how the reactor is sized.

Technology Description

Engineered improvements of SRB reactors are to be accomplished by implementing the four tasks listed below.

Task I—Selecting Optimal Media with Organic Carbon

The optimal media needs to: 1) contain a sufficient amount of organic carbon; 2) be used economically as passive SRB bioreactors; and 3) have high potential to be permeable when saturated with water. Determination of the optimal organic carbon media will be done through a literature study. A data base will be set up that will include the media technical parameters, records of use, availability, price index, etc.

Task II—Designing a Permeability and Contact Time Enhancing System (PACTES)

PACTES will ensure a good supply of organic carbon and will maintain good permeability of the organic matter throughout the predicted life of the reactor.

Task III—Designing an Organic Carbon Replaceable Cartridge System (RCS)

A replaceable cartridge system will be easy to install and replace in a bioreactor, particularly at a remote location.

To ensure that PACTES and RCS systems are compatible, their development will be symbiotic. Work on each system will include the following phases: 1) developing a list of concepts for each system; 2) narrowing the list to one or two of the most applicable solutions; 3) laboratory testing of the selected solutions; 4) preparing the design document; 5) constructing the prototype of the RCS combined with PACTES; and 6) bench-test study of the constructed prototype.

Task IV—Developing a Computer Software to Simulate SRB Activities in the Bioreactor

The software will enable a designer to efficiently design and size a bioreactor by quantifying the expected rate of organic carbon depletion and the volume of SRB activity by-products.

Status

The project was initiated in January 2000 with efforts focusing on Task I as scheduled. The literature study resulted in developing a data base, assembled with Microsoft Access, that included 88 records relevant to using various organic substances as an organic carbon source for SRB. A review of the records revealed that there have been more than two dozen organic media used for providing organic carbon for SRB. A rating of these media according to their efficiency indicates that compost, food product sewage, cow manure, and poultry waste are most suitable to supply organic carbon for SRB. Nevertheless, other factors like availability and cost must be taken into consideration when selecting organic carbon for the given location. Based on these conclusions, cow manure was recommended to be used as the organic carbon source for the efforts that will be implemented in Tasks II, III and IV.

By the end of fiscal 2000, Task II was advanced through the development of concepts for the PACTES using a mixture of cow manure prepacked in plastic-net socks, approximately one cubic foot in volume. Two kinds of mixtures are currently being considered: 1) cow manure with walnut shells; and 2) cow manure with strips of corrugated plastic and pumice stone. Walnut shells and corrugated plastic will increase the permeability and prevent settling of the mixture. In addition, walnut shells and pumice stone will provide a solid matrix for SRB growth.

Task III was also advanced to the development of concepts for the RCS that currently include a pattern of pipes filled with PACTES. The pipes will be placed in a container through which the AMD will flow in a vertical direction collinear with the axes of the pipes.

Initial work on Task IV identified an existing software, MINTEQA2, that was developed to simulate biochemical processes occurring in wetlands. This software must be modified to enable input of variables for the time and spatial coordinates.

Work on the project will continue into fiscal 2002.

ACTIVITY IV OVERVIEW

The objective of this activity is to develop, qualify, and screen techniques that show promise for cost-effective remediation of mine waste. The most promising and innovative techniques will undergo bench- or pilot-scale evaluations and applicability studies to provide an important first step to full-scale field demonstrations. Each experiment is assigned as an approved project with specific goals, budget, schedule, and principal team members.

ACTIVITY IV, PROJECT 11: PIT LAKE SYSTEM CHARACTERIZATION AND REMEDICATION FOR BERKELEY PIT—PHASE II

Project Overview

An interdisciplinary team of Montana Tech researchers is currently studying several aspects of the Berkeley Pit Lake system to better understand the system as a whole, which may lead to new or improved remediation technologies to be used during future cleanup. The information obtained from the studies will be used to predict future qualities of the water, to evaluate the natural rate of remediation, to determine if partial in situ remediation may be practical prior to expensive pump and treat remediation, and to predict water quality for similar bodies of water in the United States. The following research is being conducted on the Berkeley Pit lake: Water/Wall Rock Interactions; Bioremediation of the Berkeley Pit Lake System; and Tailings Deposition into the Berkeley Pit.

Technology Description

Organic Carbon in Berkeley Pit Sediments

Late in 1997, the Mine Waste Technology Program funded several projects to chemically and physically characterize the Berkeley Pit Lake water as a function of depth at several positions within the pit. Reports on this work are being prepared for the Berkeley Pit Characterization Project, Mine Waste Technology Program Activity IV, Project 8. The section, *Analyzing Organic Substances in the Berkeley Pit Water*, has demonstrated that the organic carbon content of the water is approximately 2 to 3 ppm. There appears to be some minor changes in total organic carbon (TOC) concentration as a function of depth in the pit lake.

Considering the sources of water for the pit lake and the similar concentrations of TOC in the in-

flow and pit lake waters, it is reasonable to assume that the organic material in the water of the Berkeley Pit Lake is typical of alpine ground and surface waters. Although not yet identified directly, it is also reasonable to assume that a major fraction of the TOC is humic material. Humic substances are well known to be important factors in controlling the chemistry of aquatic ecosystems. Humic material bind hydrogen ions, metal ions, and other organic compounds; adsorb strongly at aqueous/solids interfaces; and participate in the redox and photochemistry of surface waters.

Wall Rock/Water Interactions

To understand the processes of water-rock interaction in the pit environment, we need to know more about the mineralogy of the pit walls and how these minerals interact with rain water, oxidized (shallow) pit water, and reduced (deep) pit water. The main objectives of this project are: 1) to collect a suite of samples from the north high wall of the Berkeley pit, focusing on material that contains abundant secondary minerals (post mining oxidation products); 2) to collect a suite of samples from the walls of the Lexington tunnel (e.g., dripstones forming at acid rock drainage seeps); 3) to characterize the mineralogy of these samples by the scanning electron microscopy/energy dispersive spectrometer and x-ray diffraction; and 4) to interact selected samples with distilled water, oxidized pit water, and reduced pit water to document changes in solution chemistry (e.g., pH, metal concentration) and solid mineralogy with time.

Bioremediation of the Berkeley Pit Lake System

Very little is known about the organisms that are impacted by mine waste in the Berkeley Pit Lake system. It is known that if heterotrophic and autotrophic organisms are properly nurtured, they can bioremediate mine waste-influenced areas as a benefit of their physiological processes.

However, before any type of bioremediation of an ecosystem can begin, it is essential to gain a

fundamental understanding of the components of the microbial community. Defining the baseline community structure is the first step toward understanding the interaction of the different biota and toward assessing any improvement in biodiversity within the biotic community. Progress toward this understanding has been made clearer by previous research.

Tailings Deposition into Berkeley Pit

One potential course of action of ongoing Montana Resources operation adjacent to the Berkeley Pit is to deposit tailings into the Berkeley Pit instead of pumping them up to the Yankee Doodle Tailings Pond. As a result, a high pH tailings slurry would be mixed with the low pH Berkeley Pit water. The exact result of tailings deposition into the Berkeley Pit is not clear. This research will focus on three main areas: 1) water quality of Berkeley Pit water as tailings are deposited; 2) long-term stability of tailings/water mixture; and 3) long-term stability of tailings alone.

Status

Organic Carbon in Berkeley Pit Sediments: Total organic carbon concentrations are significantly higher in the sediments than in the water column. The source of the organic carbon must still be determined.

Wall Rock/Water Interactions: Humidity cell tests using wall rock from the Berkeley Pit and distilled water produce effluents very similar to the water currently in the Berkeley Pit in terms of dissolved metals concentrations.

Bioremediation of the Berkeley Pit Lake System: Significant dissolved metal concentrations were observed after algae found in Berkeley Pit water were grown in optimum conditions. This is important information for future in-situ remediation strategies that may be employed at the Berkeley Pit.

Tailings Deposition into Berkeley Pit: Limed tailings, when added to Berkeley Pit water on a 1:1

ratio (volume), significantly raise the pH and lower the dissolved metal concentrations, while backfilling the pit at the same time.

This project was completed, and the final report is being prepared.

ACTIVITY IV, PROJECT 12: AN INVESTIGATION TO DEVELOP A TECHNOLOGY FOR REMOVING THALLIUM FROM MINE WASTEWATERS

Project Overview

The thallium literature review was conducted as a necessary precursor study under the Mine Waste Pilot Program Activity I Issues Identification and Technology Prioritization Report to determine whether a pilot-scale demonstration of thallium removal should be performed. A similar review for arsenic (*Mine Waste Pilot Program Activity I Issues Identification and Technology Prioritization Report: Arsenic*) resulted in a very successful pilot scale demonstration of three arsenic removal technologies. Thallium removal technologies are not developed to the same state of the art as the arsenic removal technologies. Therefore, the conclusion is that further laboratory bench-scale test work and development are required before pilot-scale demonstrations are performed by MSE Technology Applications, Inc.

This research is being conducted in response to the need for bench-scale laboratory investigations to develop appropriate thallium removal technologies prior to a pilot-scale demonstration project. The question is, what technologies may be appropriate for removing thallium to levels of 1.7 ppb? Two technologies that may be able to meet the proposed thallium level are proposed for laboratory bench-scale experimental study, e.g., manganese dioxide adsorption (readily available as a waste product from zinc electrowinning operations) and reductive cementation of thallium utilizing elemental iron (a relatively inexpensive reagent available in scrap form).

Status

Preliminary research has begun. The project will be completed in March 2001

ACTIVITY IV, PROJECT 13: SULFIDE COMPLEXES FORMED FROM MILL TAILINGS PROJECT

Project Overview

No investigation has been conducted of the reactions occurring in the reduced zone of a tailings heap. Generally, it is believed that any metal oxides that are mobilized in the upper oxidized zone will be reprecipitated as sulfides in the lower reducing zones of the tailings. Numerous metal sulfides exist and may be formed in this reducing zone of the tailings. These complexes may be mobilized as the reduction-oxidation (redox) potential changes within the tailings. In the Berkeley Pit, if tailings are deposited into the Pit lake, and the system's redox potential changes over time, any metal sulfide complexes could be mobilized and enter the deep aquifer surrounding the Pit.

Status

Preliminary work has begun. The project will be completed in March 2001

ACTIVITY IV, PROJECT 14 ARTIFICIAL NEURAL NETWORKS AS AN ANALYSIS TOOL FOR GEOCHEMICAL DATA

Project Overview

This project applies to artificial neural network (ANN) analysis of geochemical and similar data sets, such as those acquired from the Berkeley Pit in Butte, Montana. There are two main types of ANN, supervised and unsupervised networks, and both lend themselves to analyses of this nature. Supervised networks are used in conjunction with or in place of conventional prediction models. They require sets of known inputs and target results or measurements. Unsupervised networks serve a useful function as data mining tools. They do not require pairs of input/target values but instead make an unbiased determination of groups or clusters that occur in the data.

Status

Preliminary work has begun. The project will be completed in March 2001.

ACTIVITY IV, PROJECT 15 IMAGING SPECTROSCOPY—AN INITIAL INVESTIGATION

Project Overview

This research project will be done in phases. The first task is to conduct a comprehensive literature search of imaging spectroscopy and its application to mining and mine waste. If the technology is found to be viable for characterizing mining-impacted areas, a second phase project may be funded.

Status

Minimal progress was made on this project due to a sabbatical taken by the principle investigator. Work is planned to begin in fiscal 2001.

ACTIVITY IV, PROJECT 16 PIT LAKE SYSTEM CHARACTERIZATION AND REMEDATION FOR BERKELEY PIT—PHASE III

Project Overview

This research project is designed to study and characterize several aspects of the Berkeley Pit lake system to gain a better understanding of the pit lake systems. The information obtained from the Berkeley Pit lake research will be used to predict future qualities of the water, to evaluate the potential for natural remediation, to determine if partial in-situ remediation may be practical prior to pump and treat remediation, to develop new or improved remediation technologies, and to predict water quality for similar bodies of water in the United States. The following areas of research and testing for the Berkeley Pit lake have been determined: Humic Remediation Potential; Algal Remediation of Berkeley Pit Water; Berkeley Pit

Aquifer Modeling; and Remediation by Photocatalysis.

Technology Description

Humic Remediation Potential

Humic substances have widely varying chemical compositions and molecular weights. These substances are generally acidic and are considered to be polymeric in structure. Humic materials are produced by the biological and chemical degradation of plant and animal matter and are often operationally separated into two water-soluble fractions, fulvic acids, and humic acids. The distinction between these two groups is a result of different molecular-weight ranges, solubilities, and the separation procedure used. The fulvic acid group has the lower molecular-weight range and higher water solubility. Chemical analyses of humic materials has consistently demonstrated the presence of a large fraction of aromatic material and carboxylic acid and phenolic functional groups. These oxygenated functional groups are responsible for the strong binding of the humic materials to mineral surfaces and the binding of metal ions in aqueous solutions.

Algal Remediation of Berkeley Pit Water

Ongoing research is beginning to help us understand the microbial ecology of the Berkeley Pit Lake System, with ever increasing information becoming available regarding the diversity of algae, protists, fungi and bacteria that inhabit this mine waste site. Defining the baseline community structure has been the first step not only toward understanding the interactions of the different groups of organisms but also toward assessing any improvement in biodiversity within the biotic community. Now that this first step has begun, this research will investigate how some of these extremophiles, specifically algae, that have been isolated from the Berkeley Pit Lake System may be used as a potential solution for bioremediation. The primary goal of this study is to determine the potential utilization of algae for bioremediation of the Berkeley Pit Lake System.

Berkeley Pit Aquifer Modeling

The water level in the Berkeley pit has risen a little more than 1 foot per month for the last several years. There are several sources of ground water and a range of ground-water qualities entering the pit: a) contaminated ground water from the underground workings in the bedrock aquifer west of the pit; b) uncontaminated ground water from the bedrock aquifer east and southeast of the pit; and c) contaminated alluvial ground water from east and south of the pit. At a water-depth of 850 feet, the rising water in the pit is presently not in contact with the alluvial aquifer, but rather, seepage faces have formed along the rim of the pit near the bedrock-alluvium contact. The rising water level in the pit will reach a depth of about 1,150 feet (100 feet above the bedrock-alluvial contact) before controls will be implemented.

Presently, a ground-water divide exists roughly coincident with Continental Drive between the Berkeley Pit and the Butte valley. Ground water and surface water north of the divide flow into the pit while ground water and surface water south of the divide flow into the Metro Storm Drain and ultimately into Silver Bow Creek. As the pit water level rises above the bedrock-alluvium contact, the ground-water gradient toward the pit will decrease, possibly shifting the ground-water divide south of the pit, thereby, diverting a portion of the ground water now flowing into the pit to the Butte valley. This would manifest itself as an increase in water levels throughout the residential area south of the pit and a flow increase in the metro storm drain.

Remediation by Photocatalysis

Numerous technologies are available for remediating acid rock drainage. These technologies include biosorption, mineral/resin adsorption, chemical precipitation, ion exchange, freeze crystallization, evaporation, and a host of others. Several of these technologies have been tested over the past decade on Berkeley Pit Lake water. Lime precipitation became recognized as the U.S. Environmental Protection Agency's Best-Determined Available Technology for remediating the Berkeley Pit water. However, the conventional process had to be modified to meet discharge standards regarding pH and manganese and

aluminum concentrations. The resulting two-stage process required an intermediate filtration step to remove precipitates that would redissolve upon continued lime addition.

In a previous study funded by the Mine Waste Technology Program, a process was developed for remediating Berkeley Pit water while simultaneously recovering the copper and zinc and producing other marketable products. This process uses a combination of the technologies listed above but has a novel approach for using ultraviolet radiation to meet the objectives. As indicated, the process uses five stages to selectively remove various metal constituents in the water by precipitation. Solid/liquid separations between the individual stages allows for the precipitates to be recovered and eventually marketed. Furthermore, the process also meets the discharge requirements of the metals including that of arsenic.

Status

Preliminary work has begun. The project will be completed in March 2001.

ACTIVITY V OVERVIEW TECHNOLOGY TRANSFER

This activity consists of making technical information developed during Mine Waste Technology Program (MWTP) activities available to industry, academia, and government agencies. Tasks include preparing and distributing MWTP reports, presenting information about MWTP to various groups, publications in journals and magazines, holding Technical Integration Committee meetings, sponsoring mine waste conferences, and working to commercialize treatment technologies.

Fiscal Year Highlights

- The MWTP Annual Report was published summarizing fiscal year accomplishments. A similar report will be published each year.

- Several MWTP professionals appeared at varied meetings to discuss the Program with interested parties. Many mine waste conferences, as well as mining industry meetings, were attended.

ACTIVITY VI OVERVIEW TRAINING AND EDUCATION

Through its education and training programs, the Mine Waste Technology Program (MWTP) continues to educate professionals and the general public about the latest information regarding mine and mineral waste cleanup methods and research.

As a result of rapid technology and regulatory changes, professionals working in the mine- and mineral-waste areas often encounter difficulties in upgrading their knowledge and skills in these fields. In recent years, the environmental issues related to the mining and mineral industries have received widespread public, industry, and political attention. While knowledge of current research and technology is vital for dealing with mine and mineral wastes, time and costs may prevent companies from sending employees back to the college classroom.

Through short courses, workshops, conferences, and video outreach, Activity VI of MWTP educates professionals and the general public and brings the specific information being generated by bench-scale research and pilot-scale technologies to those who work in mine- and mineral-waste remediation.

Fiscal 2000 Highlights

- The *Mine Design, Operations, and Closure Conference 2000*, conducted in April 2000, continued last year's interagency cooperation. The 5-day event was cosponsored by the U.S. Forest Service; U.S. Bureau of Land Management; Montana Department of State Lands; MSE Technology Applications, Inc.; Haskell Environmental Research Studies Center; several other private companies; and Montana Tech. During the conference, experts presented overviews on such topics as predictive chemical modeling for acid mine drainage, mine water quality source control, state-of-the-art containment technologies, and innovative pit reclamation. Over 130 mine operators, consultants, and professionals from the private and public sectors attended the conference.
- The Mine and Mineral Waste Emphasis Program has an enrollment of 10 students with all of them receiving funding from MWTP. This is an interdisciplinary graduate program that allows students to major in their choice of a wide variety of technical disciplines while maintaining an emphasis in mining and mineral waste.
- A group of Mine and Mineral Waste Emphasis graduate students attended the Mine Design, Operations, and Closure Conference 2000.
- A cooperative agreement is in place for work with the Haskell Environmental Research Studies Center at Haskell Indian Nations University.
- Graduate students in the Mine and Mineral Waste Emphasis Program are working on projects in Activities IV.
- As part of the Native American Initiative, Montana Tech presented five short courses: Mining and the Environment at Fort Belknap, and Acid Rock Drainage at both Fort Belknap and Salish Kootenai College. An environmental learning community was set up to house the short courses and Web courses to make them accessible to Native American communities around the country. One Web course, *Environmental Planning for Small Communities*, is on-line.
- The *Mine Design, Operations, and Closure Conference 2000*, conducted in April 2000, continued last year's interagency cooperation. The 5-day event was cosponsored by the U.S. Forest Service; U.S. Bureau of Land Management; Montana Department of State Lands; MSE Technology Applications, Inc.; Haskell Environmental Research Studies Center; several other private companies; and Montana Tech. During the conference, experts presented overviews on such topics as predictive

Future Activities

The following training and educational activities are scheduled for 2001:

- MWTP Training and Educational activities will offer the Mine Design, Operations, and Closure Conference 2001 in April 2001.

- MWTP is working on a cooperative education package for the Montana Department of Environmental Quality.
- All funded Mine and Mineral Waste Emphasis Program graduate students will work on mine waste-oriented projects as a part of their funding requirements.

FINANCIAL SUMMARY

Total expenditures during the period October 1, 1999, through September 30, 2000, were \$5,776,987, including both labor and nonlabor expense categories.

Individual activity accounts are depicted on the performance graph in Figure 29.

The cumulative authorized funding for the period was \$9,475,048.

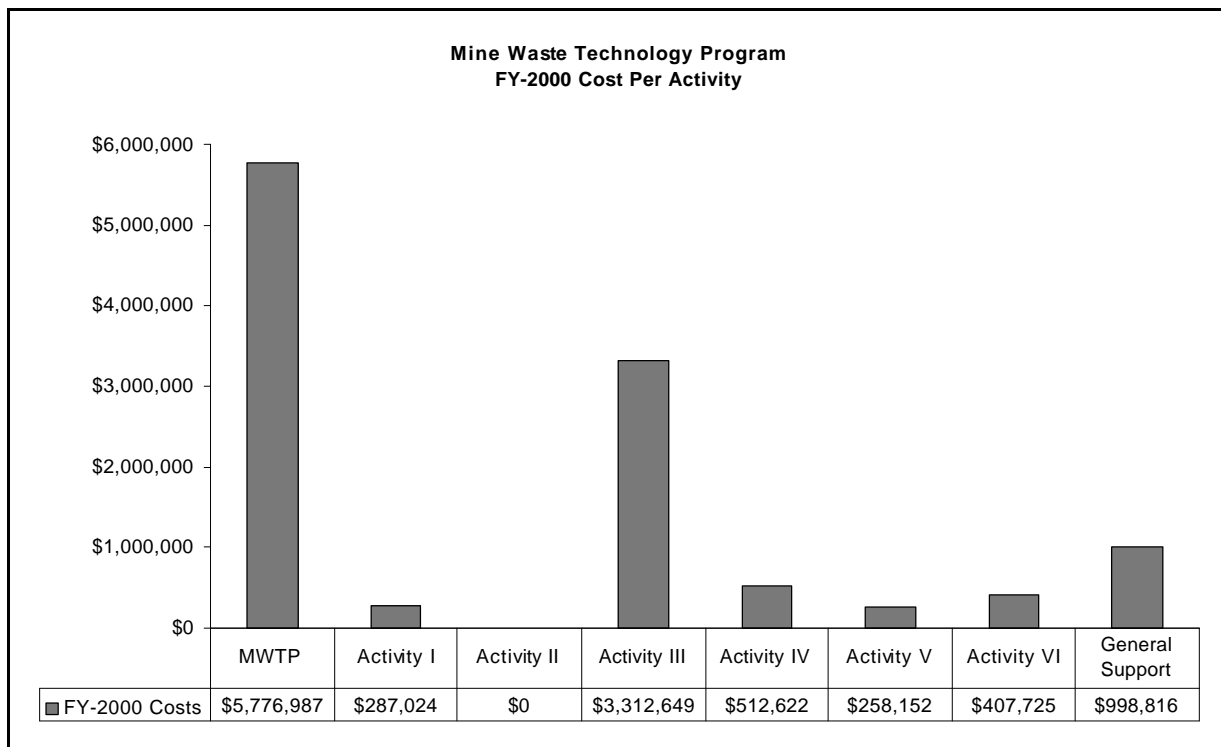


Figure 29. Mine Waste Technology Program fiscal 2000 performance graph, costs per activity.

COMPLETED ACTIVITIES

ACTIVITY III, PROJECT 1: REMOTE MINE SITE DEMONSTRATION

Project Overview

Acidic metal-laden water draining from remote, abandoned mines has been identified by the U.S. Environmental Protection Agency (EPA) as a significant environmental hazard to surface water in the western United States. In Montana alone, more than 3,000 such sites have been identified, and wastes from these mines have damaged over 1,100 miles of surface water in the State.

EPA asked MSE Technology Applications, Inc., to develop a treatment facility at one of these sites to treat acidic metal-laden water. Due to the remote nature of these locations, this facility was required to operate for extended periods of time on water power alone, without operator assistance.

The Crystal Mine, located 7 miles north of Basin, Montana, is an example of a remote mine site with a point-source aqueous discharge, which made it an ideal site for this demonstration. In addition, the site had been identified by the Montana State Water Quality Bureau as a significant contributor of both acid and metal pollution to Uncle Sam Creek, Cataract Creek, and the Boulder River. This project demonstrated a method for alleviating nation-wide environmental problems associated with remote mine sites.

Technology Description

The Crystal Mine demonstration treated a flow of water ranging from 10 to 25 gallons per minute,

approximately half of the total mine discharge. The process consisted of the following six unit operations:

- Initial Oxidation—atmospheric oxygen partially oxidizes ferrous iron to the ferric form.
- Alkaline Addition—reagents form metal hydroxide solids.
- Secondary Oxidation—atmospheric oxygen oxidizes additional ferrous iron to the ferric form.
- Initial Solid/Liquid Separation—settling ponds trap precipitated solids.
- pH Adjustment—atmospheric carbon dioxide lowers the pH.
- Secondary Solid/Liquid Separation—settling pond retains additional precipitated solids.

Results

The Remote Mine Site Demonstration Project at the Crystal Mine was conducted in the field for 2 years under all weather conditions. Construction of buildings, ponds, and associated mine site infrastructure began in late May 1994 and was completed in early August 1994. Acid mine drainage from the lower portal of the Crystal Mine began passing through the system on a full-time basis in early September 1994. Analytical data from the project showed a greater than 75% removal of toxic metals from the mine drainage. The project was closed out, and the final report was published.

ACTIVITY III, PROJECT 2: CLAY-BASED GROUTING DEMONSTRATION

Project Overview

Surface and ground water inflow into underground mine workings becomes a significant environmental problem when water contacts sulfide ores, forming acid drainage. Clay-based grouting, the technology selected for this demonstration, has the ability to reduce or eliminate water inflow into mine workings by establishing an impervious clay curtain in the formation.

Technology Description

Ground water flow is the movement of water through fissures and cracks or intergranular spaces in the earth. With proper application, grout can inhibit or eliminate this flow.

Grouting is accomplished by injecting fine-grained slurries or solutions into underground pathways where they form a ground water barrier. The Ukrainian clay-based grouting technology was selected for testing and evaluation because it offered a potentially long-term solution to acid mine drainage problems.

Clay-based grouts are visco-plastic systems primarily comprised of structure-forming cement and clay-mineral mortar. When compared to cement-based grouts, clay-based grouts offer the following advantages: better rheological characteristics, greater retention of plasticity through the stabilization period, and less deterioration during small rock movement.

Results

The Mike Horse Mine near Lincoln, Montana, was the project site. A major factor in the site selection was an identified point-source flow from

Mike Horse Creek into the mine causing acid drainage that could potentially be controlled using grouting technology.

Approximately 1,600 cubic yards of clay-based grout were injected into the fracture system adjacent to the Mike Horse Mine. The grout was pumped into boreholes using packers to ensure the proper placement of grout at selected intervals. Grout injection was initiated in September 1994 and was completed in November 1994. A second phase of grout injection was planned for the summer of 1995; however, high water dammed up within the mine caused extensive damage to the mine and to the monitoring stations used for the demonstration. As a result, Phase Two was discontinued.

From the minimal amount of monitoring data that was collected, it was determined that the total discharge from the mine was reduced by approximately 30%.

The final report was published.

ACTIVITY III, PROJECT 4: NITRATE REMOVAL DEMONSTRATION

Project Overview

The presence of nitrates in water can have detrimental effects on human health and the environment. Nitrates may be present in mine discharge water as a result of mining or other industrial activities.

To comply with federal and state water quality standards, mining companies have typically used ion exchange or reverse osmosis to remove nitrates from discharge water. However, both are expensive and generate a concentrated nitrate wastestream requiring disposal.

Technology Description

Mine Waste Technology Program (MWTP) personnel undertook an extensive search to evaluate innovative nitrate removal technologies. Of the twenty technologies screened, the following three showed the most promise in making nitrate removal more economical and environmentally responsible:

- ion exchange with nitrate-selective resin;
- biological denitrification; and
- electrochemical ion exchange (EIX).

MWTP personnel believed the best solution to the nitrate problem was some combination of the three technologies that balanced capital costs with operating costs, reliability, and minimization of wastestreams requiring disposal. Each combination had advantages and disadvantages that were addressed during the project.

Results

The Nitrate Removal Demonstration Project was conducted at the TVX Mineral Hill Mine near Gardiner, Montana. Conventional ion exchange was used to remove nitrate from the mine water and produce a concentrated brine for additional testing. Biological denitrification units and an EIX unit were used to process both mine water and concentrated nitrate brine.

The goals of the project were to remove nitrate to less than 10 milligrams per liter (mg/L) of nitrate-nitrogen ($\text{NO}_3\text{-N}$) in the effluent and to minimize the amount of waste produced. Of all the technology combinations tested, biological denitrification of concentrated nitrate brine was the most successful at meeting these goals.

The nitrate ion exchange (NIX) unit was produced by Altair, Inc. As expected, the NIX unit worked well and removed nitrate from the mine water very effectively. Input levels of 20 to 40 mg/L $\text{NO}_3\text{-N}$ were typically reduced to less than 1 mg/L. The unit also produced a concentrated brine with high levels of nitrate and chloride. Frequent equipment shutdowns and muddy mine water did not affect the operation of the NIX unit.

Biological denitrification was performed on both mine water and concentrated brine. This process worked well to eliminate nitrate in brine. Except for two process upsets, nitrate was removed to levels less than 10 mg/L $\text{NO}_3\text{-N}$. This removal rate met the project goals and was typically greater than 99%.

Biological denitrification of the raw mine water was less successful. A removal rate of approximately 50% was typically achieved. This data was taken from an operating denitrification reactor at the mine. Past data had shown that this reactor was very effective at nitrate removal. Apparently, the frequent shutdowns and startups had a detrimental effect on these reactors.

The electrochemical ion exchange unit was built by Selentec, Inc. Electrochemical ion exchange was unsuccessful at removing much nitrate from the concentrated brine because of the presence of high concentrations of a competing anion—chloride.

Electrochemical ion exchange was able to remove nitrate from the raw mine water more effectively than from the brine. Nitrate was removed at first; however, fouling of the resin by dirty water occurred quickly, and the process was rendered ineffective after one batch. Filters were installed, but the nature of the particles made filtration difficult.

The final report was published.

ACTIVITY III, PROJECT 5: BIOCYANIDE DEMONSTRATION

Project Overview

The primary use of cyanide in the mining industry is to extract precious metals from ores. The use of cyanide has expanded in recent years due to increased recovery of gold using heap leach technologies. Cyanide can be an acute poison and can form strong complexes with several metals, resulting in increased mobility of those metals. As such, cyanide in mine wastewater can contribute to environmental problems.

These potential problems have led to the development of several methods to destroy cyanide and cyanide complexes in mining wastewater. Most of these processes use chemicals to oxidize the cyanide and produce nontoxic levels of carbon dioxide and nitrogen compounds, which are relatively expensive to operate.

Technology Description

Biological destruction of cyanide compounds is a natural process that occurs in soils and dilute solutions. To take advantage of this natural destruction, a strain of bacteria was isolated by researchers at Pintail Systems, Inc. This bacteria has been tested on cyanide-contaminated mine waters and has shown degradation rates of over 50% in 15 minutes.

The main goal of this project was to use a strain of bacteria to destroy cyanide associated with precious metal mining operations. Another project goal was to develop a reactor design that would best use the cyanide-degrading effects of the bacteria to destroy cyanide from mining wastewater.

The field demonstration portion of the project was located at the Echo Bay McCoy/Cove Mine, southwest of Battle Mountain, Nevada. The mining rate at the mine exceeds 160,000 tons of ore per day. Milling of high-grade and sulfide ores occurs simultaneously with the cyanide solution heap leaching of lower grade ores. These cyanide solutions contain 500 to 600 mg/L of weak acid dissociable (WAD) cyanide with other contaminants, such as arsenic, copper, mercury, selenium, silver, zinc, and nitrate.

Results

In fiscal 1996, a field-scale unit was constructed at the McCoy/Cove Mine to degrade cyanide in an existing process stream. The unit was designed to reduce the WAD cyanide concentration from 500 mg/L to less than 0.2 mg/L at flow rates of approximately 1 gallon per minute.

A bioaugmentation phase was initiated to isolate organisms and select the ones that degrade cyanide most effectively. To initiate the project, Pintail Systems, Inc., collected water samples from the mine site to isolate indigenous organisms capable of effectively degrading cyanide and performed bioaugmentation studies at their Colorado laboratory. During the bioaugmentation phase, the bacteria were subjected to increasing concentrations of cyanide to select the most capable organisms.

The bacteria selected during the bioaugmentation process were then placed on fixed growth media in bench-scale reactors. Next, actual cyanide mine water was processed through the reactors to study the kinetics of cyanide degradation. The results from these tests were used to design the pilot-scale reactors to be used at the mine. The process train consisted of tanks where the aerobic and anaerobic bacteria were grown in large quantities. The bacteria were then pumped to the reactors for reinoculation. The cyanide solution entered the aerobic reactor first where aerobic organisms degraded a large portion of the cyanide. The solution then moved through a series of anaerobic units for further degradation. Finally, an aerobic polishing step removed the last traces. Since cyanide is known to degrade by mechanisms other than biological, a series of control reactors was installed to run concurrently with the biological reactors.

Testing of the pilot-scale unit was performed during the summer of 1997. Cyanide and heavy metals were substantially removed from the mine process water. The pH was consistently neutralized. A preliminary scale-up cost estimate indicated substantial savings over conventional technologies. The final report was published.

ACTIVITY III, PROJECT 6: POLLUTANT MAGNET

Project Overview

Personnel from the U.S. Environmental Protection Agency's National Risk Management Research Laboratory forwarded this project to the

Mine Waste Technology Program (MWTP). The concept of the pollutant magnet was to develop, produce, and test particles that have specific magnetic properties and have the ability to remove specific pollutants from a wastestream. After program personnel reviewed the project, it was dropped from MWTP due to its similarity with competing technologies that were more developed and had a nonmining specific use.

ACTIVITY III, PROJECT 7: ARSENIC OXIDATION

Project Overview

The Arsenic Oxidation Project was proposed to demonstrate and evaluate arsenic oxidation and removal technologies. The technology being demonstrated during this project was developed jointly by the Cooperative Research Center for Waste Management and Pollution Control Limited and the Australian Nuclear Science & Technology Organization (ANSTO) from Lucas Heights Research Laboratories in Lucas Heights, New South Wales, Australia.

Arsenic contamination in water is often a by-product of mining and the extraction of metals such as copper, gold, lead, zinc, silver, and nickel. This contamination will continue to grow as high-grade ores with low arsenic content are being depleted and the processing of sulphide ores with high arsenic content becomes increasingly common. In most cases, it is not economical to recover the arsenic contained in process streams because there is little demand worldwide for arsenic. Arsenic can be present in leachates from piles of coal fly ash, in contaminated ground waters, in geothermal waters, and in acid drainage from pyritic heaps resulting from the past practices of mining metallic ores.

Trivalent arsenic, arsenite, or As^{+3} compounds have been reported to be more toxic than the corresponding pentavalent arsenic, As^{+5} or arsenate forms, and much more difficult to

remove from solution. Consequently, there is a need to convert As^{+3} to As^{+5} to achieve effective arsenic removal from solution.

Technology Description

The small-scale pilot project demonstrated a two-step process for removing arsenic from contaminated mine water. The first step and primary objective of this project was to evaluate the effectiveness of a photochemical oxidation process to convert dissolved As^{+3} to As^{+5} using dissolved oxygen as the oxidant. The technology provides a method for the oxidation of As^{+3} in solution by supplying an oxidant, such as air or oxygen, and a nontoxic photo-absorber, which is capable of absorbing photons and increasing the rate of As^{+3} oxidation to the solution. The photo-absorber used is economical and readily available. Ultraviolet oxidation using high-pressure mercury lamps and solar energy was tested. The second step of this project resulted in removing As^{+5} from the solution by using an accepted U.S. Environmental Protection Agency method, adsorption using ferric iron.

Results

The field demonstration and final report were completed. The photochemical oxidation process was very effective at oxidizing arsenite to arsenate at optimum conditions in the batch mode for both the solar tests and the photoreactor tests; however, design problems with the photoreactor unit in the continuous mode would not allow ANSTO to achieve their claim of 90% oxidation of arsenite in solution. Channeling of the process waters in the photoreactor unit was the reason for poor oxidation of arsenite, and steps to correct the problem during the field demonstration were unsuccessful. Modifications to the baffle system are necessary to prevent further channeling.

All work was completed, and the final report was published.

ACTIVITY III, PROJECT 9: ARSENIC REMOVAL

Project Overview

The purpose of the Arsenic Removal Project was to demonstrate the effectiveness of two innovative technologies and the best demonstrated available technology (BDAT) to remove arsenic from mineral industry effluents to below 50 parts per billion (ppb). Table AIII, P9-1 shows the removal and economic analysis of these tests. Two of the treated effluent streams were from the ASARCO East Helena lead smelter; the scrubber blowdown water contained >3 grams per liter arsenic and other associated metals, and the water treatment thickener overflow water contained approximately 6 parts per million arsenic. A third stream from the TVX Mineral Hill Mine 1,300-foot portal ground water contained approximately 500 ppb arsenic.

Table AIII, P9-1. Removal and economic analysis for Activity III, Project 9.

Technology	Scrubber Blowdown (> 3 g/l As)	Thickener Overflow (~6 ppm)	Portal Ground Water (~500 ppb)	Cost/1000 gallons*
Mineral-Like Precipitate	< 10 ppb	< 10 ppb	< 10 ppb	\$0.30
Alumina Adsorption	—	200 ppb	21 ppb	\$0.70
Ferrihydrite Adsorption	—	< 50 ppb	< 50 ppb	\$0.55

*Cost analysis is based on treating 300 gpm of ground water containing 500 ppb arsenic. The accuracy of the measurement is +/-30%.

Technology Description

Mineral-Like Precipitation

The concept of this process is to strip arsenic (as arsenate) from solutions in a manner to produce mineral-like precipitated salts. The concept is to substitute arsenate into an apatite structure, thereby, forming a solid solution compound that would be thermodynamically stable in an outdoor storage environment.

Alumina Adsorption

In this technology, arsenic is removed from solution by adsorbing it onto the surface of aluminum oxide over a specific pH range. After absorption, reagents are added to the alumina to desorb the arsenic into a concentrated brine. The concentrated arsenic brine solution is then treated using an iron adsorption technology to remove and stabilize the arsenic. The activated alumina in the process is recycled following the desorption process by treatment with sodium hydroxide.

Ferrihydrite Adsorption

Ferrihydrite technology is the BDAT. For ferrihydrite adsorption to occur, ferric iron (Fe^{+3}) must be present in the water. Dissolved arsenic is removed by a lime neutralization process in the presence of the ferric iron, which results in the formation of arsenic-bearing hydrous ferric oxide (ferrihydrite).

Results

All three technologies (iron coprecipitation, alumina adsorption, and mineral-like precipitation) showed favorable results for arsenic removal using ground water; however, using industrial process wastewater, only two of the technologies (mineral-like precipitation and ferrihydrite adsorption) were capable of removing arsenic to below discharge standards. The complex chemistry of the industrial wastewater had a profound effect on arsenic removal using alumina adsorption.

All work was completed, and the final report was published.

ACTIVITY III, PROJECT 11: CYANIDE HEAP BIOLOGICAL DETOXIFICATION DEMONSTRATION

Project Overview

Cyanide is used in the mining industry to dissolve precious metals from ore but can contribute to environmental problems. This has led to the development of technologies to degrade cyanide and cyanide complexes in mine wastewater and spent ore heaps. Most of these processes use chemicals to oxidize cyanide and are expensive to operate. Therefore, biological detoxification has been proposed as an alternative to chemical treatment for decommissioning heap leach operations.

Three biological technology providers were contracted to participate in a long-term study in which the effectiveness of their technology was compared with hydrogen peroxide and process rinse water.

Technology Description

This project demonstrated four biological technologies. Project objectives were to:

- reduce the concentration of the effluent weak acid dissociable (WAD) cyanide to meet National and State regulatory standards within a reasonable period;
- determine final affects of biological treatment on related discharge parameters (pH, sulfates, nitrates, metals, and gold recovery); and
- determine technology cost compared to conventional detoxification methods. Column testing began on December 3, 1998, and operated 158 days until May 17, 1999.

Results

The standard hydrogen peroxide rinse column was demonstrated to have the highest WAD cyanide degradation rate. The regulatory limit of <0.2

milligrams per liter was reached in 36 days. The process rinse water column showed a cyanide degradation curve of approximately one-third as high as the hydrogen peroxide rinse column.

One technology provider reached the regulatory limit in 151 days. The remaining three biological processors were slightly quicker than the process rinse water and were approaching the regulatory limit at termination of the demonstration.

All work was completed, and the final report was published.

ACTIVITY III, PROJECT 17: LEAD ABATEMENT DEMONSTRATION

Project Overview

The foremost cause of childhood lead poisoning in the United States is the ingestion of lead-based paint found in older housing. The overall objective of this demonstration was to obtain cost and performance data on an innovative set of technologies capable of removing lead-based paint from interior decorative wood in residential housing with minimal damage to the underlying substrate and no residual hazardous waste.

Technology Description

The technologies evaluated included the paint removal system PR-40/LEADX™/PR-40AFX™ and a carbon dioxide blasting technology.

Results

The paint removal system PR-40/LEADX™/ PR-40AFX™ was demonstrated to effectively remove lead-based paint and/or lead-based varnish from interior decorative wood with minimal apparent damage to the wood substrate within certain operational limitations. The product proved effective when previous paint/varnish layers were between six to eight layers. Other wall coverings

beneath the paint surface (i.e., wallpaper or wall texturing) further impacted penetration of PR-40/LEADX™/PR-40AFX™.

The carbon dioxide blasting technology was effective in removing the lead-based paint only in areas where PR-40/LEADX™/PR-40AFX™ had achieved full penetration of all paint layers. However, the blasting technology produced an unsatisfactory erosion of soft wood leaving the surfaces feathered and/or gouged.

ACTIVITY III, PROJECT 18: GAS-FED SULFATE-REDUCING BACTERIA BERKELEY PIT WATER TREATMENT

Project Overview

Sulfate-reducing bacteria (SRB) are a well-known, effective method for treating acid mine drainage (AMD). With the proper conditions of solution temperature and oxidation/reduction potential, and with suitable nutrients available to the SRB, sulfate is electrochemically reduced to sulfide, which forms insoluble precipitates with many metals. In addition, alkalinity is produced that serves to raise the solution pH. Previous and current Mine Waste Technology Program projects have successfully demonstrated SRB in remote locations with the goal of providing improved water quality at low cost. Advances have been made in engineered systems utilizing SRB, particularly in the area of providing cheap nutrients to the bacteria, which significantly enhance overall system economics. These advances increase the possibility of utilizing SRB as part of an AMD treatment system in which selected metals are separated and recovered for resale, offsetting overall treatment costs. This project demonstrated and evaluated a process with the potential to profitably recover copper, zinc, and sodium hydrosulfide from Berkeley Pit water.

Technology Description

Biomet Mining Corporation of Vancouver, British Columbia, has patented a method utilizing combustion products from natural gas as nutrients for SRB, called the Biosulfide process. This cheap source of nutrients has enabled Biomet to show favorable economics in recovering copper and zinc products from AMD at pilot-scale at several locations in North America. Copper is recovered directly as copper sulfide using hydrogen sulfide gas produced by SRB. Following a pH adjustment using the alkalinity produced by the SRB, hydrogen sulfide gas is used to recover zinc as zinc sulfide. Other products, including sodium hydrosulfide and sulfuric acid, can be produced with downstream processing if the economics at a specific location are favorable.

Results

Bench-scale miniplant testing began at the MSE Technology Applications, Inc. (MSE) facility in October 1998. Biomet performed laboratory tests to determine initial pH and oxidation/reduction potential conditions for copper and zinc separation/recovery from September to November 1998. Biomass development was performed at MSE with the pilot-scale system between December 1998 and May 1999. Biomet moved the pilot system to the Berkeley Pit in May 1999, and MSE had virtually no involvement in the project after that time due to budgetary constraints. Pilot-scale operation continued at the Berkeley Pit until September 1999, at which time the pilot system was shut down with tentative plans to restart in April 2000. Pilot-scale operation was plagued with operational problems, particularly related to the performance and reliability of the natural gas burner and to the sulfate reduction performance of the bacteria. At the direction of the U.S. Environmental Protection Agency, MSE terminated support of the project in December 1999.

ACTIVITY IV, PROJECT 1: BERKELEY PIT WATER TREATMENT

Project Overview

Bench-scale research on treating water from the Berkeley Pit was performed at Montana Tech of the University of Montana, in Butte, Montana.

The Berkeley Pit is an abandoned open-pit copper mine in Butte that has been filling with acidic water since pump dewatering of adjacent underground mines ceased in 1982. Flow into the Berkeley Pit has varied from approximately 7.5 million gallons per day initially to a current rate of approximately 2.5 million gallons per day.

The water in the Berkeley Pit was chosen for this project due to its accessibility, abundance, and the chemical similarities between it and other acidic mine waters. Studies had been conducted since 1986 on the Berkeley Pit water, and substantial analytical data had been developed, providing a foundation for this project.

Technology Description

This project addressed treatability of the acid mine water that is accumulating in the Berkeley Pit. Appropriate treatment techniques were identified and developed. The overall goal was to evaluate technologies that produce clean water, allow for safe waste disposal, and recover selected metals for resale. Technologies were evaluated by considering their effectiveness, technical feasibility, and potential for technology transfer to similar sites.

Experimental testing consisted of four phases:

Physical oxidation, neutralization, and metal removal—this phase consisted of using alkaline reagents such as lime, limestone, or soda ash to

neutralize the water and cause metals to precipitate as hydroxides. During neutralization, the water is aerated to oxidize Fe^{+2} to Fe^{+3} , thereby, enhancing sludge settling characteristics and promoting adsorption reactions. Metals removal efficiency and reaction kinetics were studied.

Metals separation and recovery—this phase was a two-stage hydroxide precipitation process. Sulfide and hydroxide precipitation were combined for more complete removal of metals. In other tests, metal sulfides were precipitated first to recover metal value, and scrap iron was used to cement copper before neutralization.

Use of milling waste—this phase consisted of adding tailings slurry (primarily silicates, clay, lime, and limestone) directly to the Berkeley Pit water. This partially neutralized the water and removed some of the heavy metals. This in situ neutralization could potentially reduce reagent consumption and sludge formation for subsequent processing.

Diversion and treatment of various inflow water sources—this phase consisted of investigating numerous water sources to determine the feasibility of diverting inflow water for treatment. Of the water that flows into the Berkeley Pit, one-third is surface water from the Horseshoe Bend area, and two-thirds is underground water that has penetrated through the mines and surrounding rocks.

Results

All work for this project was completed, and the final report was published.

ACTIVITY IV, PROJECT 2: SLUDGE STABILIZATION

Project Overview

The Sludge Stabilization Project for mine waste was a bench-scale research project conducted at Montana Tech of the University of Montana.

The purpose of this research project was to study the properties and stability of sludges generated by remediation of acid mine waters. Results of the study were used to determine the best methods for sludge handling and disposal. One source of acid mine water being studied was from the Crystal Mine located approximately 7 miles north of Basin, Montana. The other source was the water from the Berkeley Pit in Butte, Montana. Besides being acidic, these waters contain toxic concentrations of iron, manganese, copper, zinc, arsenic, and sulfate, which is typical of many hard rock mining operations throughout the western United States.

Past research on remediating acid mine water has focused primarily on water treatment techniques, and little emphasis has been placed on the stability of the sludge that is generated. To address this issue, faculty at Montana Tech of the University of Montana, with expertise in chemistry, geochemistry, metallurgy, and environmental engineering, formed a research team to study the properties and stability of this sludge.

Technology Description

The three types of sludge studied were: base-initiated sludge, inorganic sulfide-initiated sludge, and sulfate-reducing bacteria-initiated sludge. Appropriate solid-liquid separation techniques were used to isolate the solid phases for chemical characterization and stability tests.

Chemical characterization studies included quantifying the various element-solid associations, i.e., adsorbed, surface-precipitated, and coprecipitated contaminants. These studies then identified and quantified the divalent and trivalent

forms of iron and the trivalent, pentavalent, and methylated forms of arsenic. Once analytical techniques were verified for each of the sludges, they were applied to as-generated sludge and aged sludge.

Based on the chemical properties of these sludges, various storage environments were proposed and evaluated. The sludge stability research included standard regulatory tests and specifically designed tests, e.g., biostability tests, based on the selected specific disposal options, including storage in the natural environment. The results of these tests were translated into stability-enhancement studies, including the effect of aging the sludge in a temporary storage environment and treating the sludge with chemical additives before final storage.

The results of this sludge characterization and stability study identified characterization techniques and stability procedures that have application to sludges generated through other water-treatment procedures.

Results

All work for this project was completed, and the final report was published.

ACTIVITY IV, PROJECT 3: PHOTOASSISTED ELECTRON TRANSFER REACTIONS RESEARCH

Project Overview

Research efforts under the Mine Waste Technology Program for the remediation of mine wastewaters have focused primarily on removing toxic heavy metal cations from solution. However, little attention has been given to toxic anions that can be associated with the heavy metal cations.

Results

All work for this project was completed. The final report was revised and published.

ACTIVITY IV, PROJECT 3A: PHOTOASSISTED ELECTRON TRANSFER REACTIONS FOR METAL-COMPLEXED CYANIDE

Project Overview

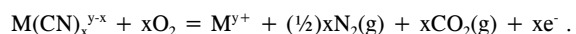
Previous research efforts under the Mine Waste Technology Program for the remediation of mine wastewaters predominantly focused on removing toxic heavy metal cations from solution. This was accomplished with chemical processes that generated heavy-metal sludges that were then removed from the water stream by solid-liquid separation processes. However, many of the anions associated with the heavy metal cations in the wastewater are also toxic but remain in solution even after the sludge is generated and separated. In this project, the remediation of metal-complexed cyanide is being investigated using several photolytic methods with the intent to identify and enhance naturally occurring remediation processes.

Overwhelming evidence shows that natural processes occur to heal environmental scars caused by mining activities. These processes include electron-transfer reactions that lower the concentrations of the anionic mobile toxic constituents in surface and ground waters through interactions with electromagnetic radiation (predominantly ultraviolet radiation but some visible light) from the sun. However, such direct natural photolytic processes suffer at night, on cloudy days, and in winter months. During these periods, artificial radiation sources are needed for sustainment. Furthermore, because the photolytic processes usually proceed slowly, catalysts are used to absorb the radiation and transfer the energy to the reactants to remediate the water within more acceptable time frames. Such photocatalysts are either solid semiconductors (heterogeneous

photocatalysts) or dissolved radicals in solution (homogeneous photosensitizers).

Technology Description

Background—When electromagnetic radiation is absorbed, electrons in the absorbing species pass from a singlet ground state (S_0) to an excited electronic state (S_1). As long as the electron remains in the excited state, the absorbing species are more susceptible to their chemical environment and are, therefore, more apt to participate in electron-transfer reactions. The absorbing species undergo photoreduction when it donates the excited electron. Conversely, photooxidation occurs when the absorbing species accept an electron. In either case, the photoreduction and photooxidation reactions can lead to the destruction of the mobile toxic constituent. For metal-complexed cyanide, only photooxidation can be used and in a reaction similar to cyanide photooxidation (see Activity IV, Project 3) where carbon dioxide and nitrogen gases are reaction products:



Direct Photolysis—In this process, the mobile toxic constituent being remediated must absorb the electromagnetic radiation. Although this phenomenon is rare, it does occur with some metal-complexed cyanides but is dependent on the solution conditions. Research was conducted to identify these conditions.

Homogeneous Photolysis—In this process, aqueous photosensitizers absorb the electromagnetic radiation and then transfer the photon energy to the mobile toxic constituents being remediated. Because the process occurs in bulk solution, its kinetics are dependent on the solution conditions and the concentrations of the photosensitizers and the mobile toxic constituents. When the aqueous photosensitizer is not consumed during the process, it is referred to as homogeneous photocatalysis. In this regard, research is being conducted to identify the conditions needed for using either homogeneous photosensitizers or homogeneous photocatalysts for metal-complexed cyanide remediation.

Heterogeneous Photocatalysis—In this process, solid semiconductors are used to absorb the electromagnetic radiation and then transfer the photon energy to the mobile toxic constituent being remediated. However, electron transfer reactions can only occur if the mobile toxic constituent is adsorbed at the surface of the semiconductor. Thus, reaction kinetics are dependent on the mobile toxic constituent concentration as well as the rate of adsorption of the constituent, the available surface area of the semiconductor, and the rate of desorption of the reaction products. Consequently, reaction kinetics can be three orders of magnitude slower than reactions with homogeneous photolysis.

Nevertheless, reaction efficiencies are usually higher with heterogeneous photocatalysis due to the higher efficiency of photon capture and the increased *life* of the electron in the excited state. This is ultimately attributed to the properties of the semiconductor. With semiconductors, electrons are promoted from the valence band and into the conductance band across a band gap. The photon energy must be greater than or equal to the band gap energy. Excited electrons in the conductance band can then be donated to the mobile toxic constituent to induce its reduction. Likewise, the electron vacancy or *hole* in the valence band can accept electrons from the mobile toxic constituent and, thereby, induce its oxidation. The process is similar to the process described earlier; however, it is evident that solution conditions must also be well-defined to control reactant adsorption and product desorption. In this regard, studies are being conducted to optimize these conditions for metal-complexed cyanide oxidation reactions. Currently, only anatase (TiO₂) is being investigated because it has the highest known efficiency of semiconductors.

Results

This project was a continuation of the nitrate and cyanide project (Activity IV, Project 3) but with the inclusion of photolytic research on metal-complexed cyanides. The final report was published.

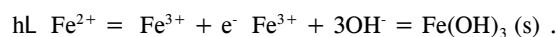
ACTIVITY IV, PROJECT 3B: PHOTOASSISTED ELECTRON TRANSFER REACTIONS FOR BERKELEY PIT WATER

Project Overview

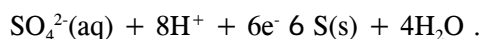
See Activity IV, Project 3A for Project Overview.

Technology Description

Background—When electromagnetic radiation is absorbed, electrons in the absorbing species pass from a singlet ground state (S₀) to an excited electronic state (S₁). As long as the electron remains in the excited state, the absorbing species are more susceptible to their chemical environment and are, therefore, more apt to participate in electron-transfer reactions. The absorbing species undergo photoreduction when it donates the excited electron. Conversely, photooxidation occurs when the absorbing species accept an electron. In either case, the photoreduction and photooxidation reactions can lead to the precipitation of mobile toxic constituents. For example, ferrous cations can be precipitated as ferri-hydroxide after being photooxidized to ferric cations:

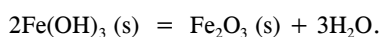


This reaction mechanism may account for the natural precipitation events observed in Berkeley Pit water. Once the iron is precipitated and separated, photolysis and/or conventional hydrometallurgical processes can then be used to recover the valuable mobile toxic constituents. On the other hand, a photoreduction reaction is exemplified by sulfate conversion to elemental sulfur:



Clearly, acid mine waters can be remediated through photolysis. However, it is important to note that several competing processes may occur and must be prevented and/or minimized to maximize the efficiency of photoassisted electron transfer reactions.

Nevertheless, reaction efficiencies are usually higher with heterogeneous photocatalysis due to the higher efficiency of photon capture and the increased *life* of the electron in the excited state. This is ultimately attributed to the properties of the semiconductor. With semiconductors, electrons are promoted from the valence band and into the conductance band across a band gap. The photon energy must be greater than or equal to the band gap energy. Excited electrons in the conductance band can then be donated to the mobile toxic constituent to induce its reduction. Likewise, the electron vacancy or *hole* in the valence band can accept electrons from the mobile toxic constituent and, thereby, induce its oxidation. The process is similar to the process described earlier; however, it is evident that solution conditions must be well-defined to control reactant adsorption and product desorption. In this regard, studies are being conducted to optimize these conditions for metal-complexed cyanide oxidation reactions. For now, both hematite (Fe_2O_3) and anatase (TiO_2) are being investigated. Hematite is important because it can actually be formed by recycling the precipitated ferrihydrite:



Whereas, the anatase is important because it has the highest known efficiency of semiconductors.

Results

The final report was published.

ACTIVITY IV, PROJECT 4: METAL ION REMOVAL FROM ACID MINE WASTEWATERS BY NEUTRAL CHELATING POLYMERS

Project Overview

A bench-scale research project was conducted at Montana Tech of the University of Montana to eliminate or minimize some current economic or technical difficulties that exist in treatment technologies for acid mine wastewater. The novel technology was based on neutral chelating polymers that can have their chelating property turned on and off. The chelate switch was based on known electrochemical or photochemical properties of electrically conducting polymers.

Technology Description

Chelates are chemical substances that have more than one binding site on the molecule. These added binding sites attach a molecule to a metal ion more strongly than a single binding site. The result is that chelates can be very effective at removing metal ions from wastewater. Chelates can be ionic or neutral. Ionic chelates exchange a cation (H^+ or Na^+) for the metal ion removed from the solution. Neutral chelates are electrically neutral and do not add material to the solutions when the metal ions are removed.

The removal of metal ions from aqueous solutions is presently accomplished by a variety of chemical and electrochemical processes. These techniques have distinct advantages in the appropriate situations (pH range, concentration range, matrix composition, etc.); however, they may not be practical under less-than-optimum operating conditions.

The goal of this project was to develop an alternate technology that required no additional chemicals, could produce a marketable product (such as pure metals), and could reduce costs and waste volume. The research project was a collaborative effort between academic and government resources, including the Haskell Indian Nations Universities' Haskell Environmental Research Studies Center. Initially, the project focused on the design of chelating polymer systems for laboratory study and for theoretical study (molecular modeling). The first polymer systems were based on current literature information. Modeling results were compared to experimental and literature results as a means to test the validity of the theoretical data.

The validated modeling procedure was used to design and test a variety of neutral chelating systems for their capability to remove metal ions and associated anions from acid mine wastewater. The neutral chelating polymers determined to be most effective for water cleanup by the preliminary experimentation and the modeling studies were studied more thoroughly. The polymeric systems were evaluated for their removal efficiencies, contaminant capacity, ruggedness, ease of use, and cost effectiveness. Other important parameters identified in the preliminary studies were also used in the systems evaluations.

A more detailed process evaluation procedure was developed from the results of the refined experimentation. The selected polymeric system was then completely studied using a variety of synthetic and actual mine wastewater.

Results

All work for this project was completed, and the final report was published.

ACTIVITY IV, PROJECT 5: REMOVAL OF ARSENIC AS STORABLE STABLE PRECIPITATES

Project Overview

The objective of this project was to strip arsenic from solutions in such a way as to produce apatite mineral-like precipitated products that are stable for long-term storage in tailing pond environments. Substitution of arsenic into an apatite structure will provide a solid solution mineral compound that is environmentally stable for outdoor pond storage.

Technology Description

Earlier research demonstrated that a precipitation technique is effective in removing arsenic (to low micrograms per liter concentrations) from aqueous solutions [U.S. Environmental Protection Agency (EPA)-supported project]. The precipitation is conducted in a way to form a solid solution compound containing arsenate and phosphate in an apatite mineral-like phase. This solid is stable to EPA's toxicity characteristic leachate procedure, and more importantly, the solubility is one to two orders of magnitude less than calcium arsenate in aqueous solutions over the pH range of 9 to 12 (the range of pH values maintained in tailing ponds).

In the early 1980s, it was demonstrated that lime precipitation of calcium arsenate with subsequent storage in a tailings pond environment is unacceptable because at pH levels above approximately 8.5, calcium arsenate will be

converted to calcium carbonate (by carbon dioxide in air) with the release of arsenic into the aqueous phase. Removal of arsenic by precipitation as calcium arsenate has been discontinued by industry and has been replaced by ferric arsenate precipitation (EPA's Best Demonstrated Available Technology for arsenic-bearing solutions). However, even though low concentrations of arsenic in solutions can be achieved by ferric precipitation, it has been demonstrated that the removal from solution is actually an adsorption phenomena. Therefore, long-term stability of such residues in tailings pond environments may not be appropriate, hence, the need for the present study.

Stability of Mineral-Like Residues—Montana Tech of the University of Montana researcher's approach to arsenic storage was to form a mineral-like phase that showed equilibrium-phase stability under tailings pond environmental conditions. If equilibrium-phase stability was achieved (for a given environment), then long-term stability would be ensured (at least for as long as the environmental conditions were maintained). This project was supporting an intensive investigation of the formation of arsenic precipitates in two systems, i.e., the calcium-arsenic-phosphate (apatite-like solid solutions of arsenate and phosphate) system, and the ferric-arsenic-phosphate (phosphoscorodite-like solid solutions of arsenate and phosphate) system. Both of these systems showed great promise for industrial application, if long-term stability could be demonstrated.

Results

The precipitation *recipe* was applied to two industrially contaminated waters, and the long-term stability of the resulting products were tested. Successful demonstrations resulted in a new way to treat arsenic-bearing wastewaters and mine drainage solutions.

All work for this project was completed, and the final report was published.

ACTIVITY IV, PROJECT 7: BERKELEY PIT INNOVATIVE TECHNOLOGIES PROJECT

Project Overview

The purpose of the Berkeley Pit Innovative Technologies Project was to provide a test bed for high risk/innovative technologies for the remediation of Berkeley Pit water. The project focused on bench-scale testing of remediation technologies to help assist in defining alternative remediation strategies for the U.S.

Environmental Protection Agency's (EPA) future cleanup objectives for Berkeley Pit waters.

Individuals, companies, or academic institutions with existing remediation technologies were invited to demonstrate their process for the project and write a report summarizing their process including the results of their bench-scale test. A copy of the report from each test was forwarded for evaluation by the EPA Region VIII field office, and the EPA National Risk Management Research Laboratory.

Results

Nine demonstrations were completed and reports are available.

ACTIVITY IV, PROJECT 8: PIT LAKE SYSTEM—CHARACTER- IZATION AND REMEDIATION FOR THE BERKELEY PIT

Project Overview

An interdisciplinary team of Montana Tech of the University of Montana researchers undertook a

preliminary study of several aspects of the Berkeley Pit to gather specific information about that pit lake system and to gather information that could be generally applied to all pit lakes.

In this work, the chemical and biological characteristics of the water and sediments in the Berkeley Pit were studied to provide water quality data that can be used to predict future water quality, to evaluate the potential for natural remediation by bacteria such as sulfate-reducers, and to determine if partial in situ remediation would be practical prior to the pump and treat technologies prescribed in the U.S. Environmental Protection Agency's Record of Decision.

To provide the water and sediment for the characterizations, the Montana Bureau of Mines and Geology sampled the water at two locations and at depths from the surface to the bottom (0 to 1,200 feet) at set intervals. Sampling was also done in both the spring and the fall to account for climatic effects on surface water quality.

Results

The water chemistry of the Berkeley Pit lake varies with the volume of water entering it from various sources and the changes in the seasons. The amount of metals precipitated from the surface water layer depends on the area of the water surface exposed to the air and the climatic changes associated with the four seasons. The chemistry of the deep water is relatively constant throughout the year.

Organic carbon, a food source for bacteria is present in the water. The concentration of organic carbon is relatively that of the natural occurring springs in the area of the Berkeley Pit.

No sulfate-reducing bacteria activity was detected in the water or the sediments. However, a number of fungi and yeasts were isolated, and these will be further studied.

The report for this study is complete. This work lead to the more specific research presented in Activity IV, Projects 9, 10, 11, and 16.

ACTIVITY IV, PROJECT 9: PIT LAKE SYSTEM—DEEP WATER SEDIMENT/PORE WATER CHARACTERIZATION AND INTERACTIONS

Project Overview

Research under this project involved collecting various water and solid samples from the Berkeley Pit to characterize them and formulate a conceptual environmental model of this well known pit lake.

The work involved collecting deep water-upper layer sediment samples (600 to 700 feet below surface), collecting subsurface sediment/pore water samples (717 feet below surface), characterization and speciation of these sediment solids and pore water, and modeling the system to understand the controlling sediment forming reactions.

Results

Significant differences did not appear in the elemental content of the upper water column and the deep water (near-sediment) solution. Iron shows a slight (approximately 5%) increase in concentration with depth. The ferrous-to-ferric ratio shows an increase from the surface to approximately 100 feet; the ratio then remains constant from 100 to 717 feet. Sulfate showed a generally increasing concentration as a function of depth. The dissolved oxygen concentration was relatively high near the surface, dropped dramatically from 2 to 18 feet, and then rose to levels exceeding the surface level. It then became relatively constant with increasing depth from approximately 100 feet to near the sediment surface. The dissolved oxygen data appears to suggest that surface water turnover may have occurred down to the 100-foot level; however, additional data is required to confirm this conclusion.

Pore water is the water present within the sediments. This water was separated as a function of depth into a series of samples. The pore water was not clean and had appreciable elemental content. Pore water had lower concentrations of aluminum, zinc, manganese, magnesium, arsenic, potassium, and phosphorus than deep water 3 feet above the sediments. Ferrous iron concentrations in the pore water were as much as four times higher in the upper sediment layers than in the deep water. The reaction of potassium jarosite and/or schwertmannite with organic carbon to form ferrous species appears to be feasible for the conditions existing in the sediments, and it is the likely reaction controlling the ferrous concentration in the pore water.

Sediment solids showed varying composition trends. Elements that showed decreasing concentration with depth include arsenic, calcium, iron, magnesium, phosphorus, lead and sulfur. The sediments were composed of detrital and precipitated compounds. The major precipitated compounds were jarosite and gypsum. The major detrital compounds were quartz, biotite and muscovite, which are predictable wall rock element at the Berkeley Pit. It was observed that the precipitated materials had a higher concentration at the surface of the core, which suggests that the precipitated solids formed in the water column and settled to the sediment surface. With time, wall rock joined the sediments and diluted them with detrital materials.

All work was completed, and the final report was published.

ACTIVITY IV, PROJECT 10: PIT LAKE SYSTEM—BIOLOGICAL SURVEY OF BERKELEY PIT WATER

Project Overview

The purpose of this research was to begin to gain an understanding of the microbial ecology of the Berkeley Pit lake system and to provide necessary data for bioremediation studies of this pit lake and others. The study goals were to determine species diversity and numbers for organisms present in the pit lake system and to begin to understand their potential role in bioremediation.

Results

The research shows that bacterial abundances are high throughout the surface water column; on average, approximately 116,000 bacteria per milliliter were found, which is only nine times less than levels in a freshwater lake. Water samples from a lower depth contain far fewer bacteria (7,000 per milliliter). Sixteen morphotypes of heterotrophic protists were identified. Very few live cells were found in fresh samples of water and sediments, suggesting that active populations are rare and most may exist as cysts, particularly in deeper anaerobic layers. The sulfate-reducing bacteria that were expected to be found in the water and sediments did not exist.

All work was completed, and the final report was published.

KEY CONTACTS

U.S. Environmental Protection Agency:

Roger C. Wilmoth
U.S. Environmental Protection Agency
Office of Research and Development
National Risk Management Research
Laboratory
26 W. Martin Luther King Drive
Cincinnati, OH 45268

Telephone: (513) 569-7509
Fax: (513) 569-7471
wilmoth.roger@epa.gov

U.S. Department of Energy:

Madhav Ghate
U.S. Department of Energy
National Energy Technology Laboratory
P.O. Box 880
3610 Collins Ferry Road
Morgantown, WV 26507-0880

Telephone: (304) 285-4638
Fax: (304) 285-4135
mghate@netl.doe.gov

MSE Technology Applications, Inc.:

Creighton Barry, Program Manager
MSE Technology Applications, Inc.
P.O. Box 4078
Butte, MT 59702

Telephone: (406) 494-7268
Fax: (406) 494-7230
cbarry@mse-ta.com

Montana Tech:

Karl E. Burgher, Montana Tech MWTP
Project Manager
Montana Tech of the University of Montana
1300 West Park Street
Butte, MT 59701-8997

Telephone: (406) 496-4311
Fax: (406) 496-4116
kburgher@mtech.edu